CALCULATION OF CARBON DIFFUSION FORCEMENTATION OF GEAR WHEELS

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The paper deals with the determination of the precise calculation of carbon diffusion and carbon prediction in the production of gear wheels cementation from steel by Czech standard (steel CSN 14220, or ASTMA 506). In the research part of the paper, considerable attention is paid to the determination of the necessary data for calculating the cementation, especially the mass- the carbon-binding coefficients β_C and the determination of the value of the carbon diffusion coefficient D_C. A diffusion analysis was performed with respect to its kinetics. At the same time, the essence of diffusion in metals is described, and attention is paid to the cementation of the selected steel, i.e the diffusion conditions of its cementation. According to industrial experience, three cementation times for steel gears were chosen. The main attention was paid to calculating the diffusion and distribution of carbon in the wheel teeths under different conditions of cementation. In addition to the definite input variables of the diffusion process, the mass-carbon β determined on the basis of WYSS recommendations [Wyss 1978]. This factor affects the thickness of the diffusion boundary layer at the interface of the metal atmosphere resulting from carbon transfer and defines the amount of carbon atoms that receives the surface of the steel from the carbonaceous atmosphere. Also, the significant diffusion coefficient D was determined based on the findings [Pisek 1974] and [Brandes 1992]. Based on the diffusion production parameters included in the calculation, experimental cementation of gears was performed under different conditions. The layer of overfilled carbon in wheel teeth, their measurement and statistical evaluation were monitored. The basis was to achieve 0.4 wt. % C in three types of diffusion layers (0.6 mm, 0.8 mm and 1.0 mm). Gears after cementation were hardened and tempered. On these technologically processed wheels, microhardness was monitored, the CHD 550 value and the microstructure at various points of the teeth of the wheels were determined.

KEYWORDS

cementation, steel, carbon, diffusion, gear, wheels

1 INTRODUCTION

Diffusion is a thermal-physical process that is applied in many engineering proceses. In mechanical engineering, carbon diffusion is often used to heat-surface treatment steel parts - for example, cementation - for structural components (eg gears, shafts) made of steel to provide hardness and strength while maintaining a tough core. The tough core provides low carbon steel to about 0.2%. However, the steel containing 0.2% C is not a guarantee to get the necessary amount of martensite. The theoretical amount of carbon for steel quenching (hardening) is 0.3%. More favorable for quenching (hardening) is the carbon content - about 0.7 to 0.8%. Therefore, the surface of the steel structural component must be saturated with carbon - cementing. However, the cementation would not produce the desired result without subsequent heat treatment, so called quenching. E.g. thepresent thermal treatment of gears is accomplished by cementation in batch furnaces or in vacuum, followed by martensitic hardening and low temperature tempering. The martensitic structure in the surface layer of the gear wheel increases the hardness and abrasion resistance of the surface.

Subsequently, attention is paid directly to carbon steeping, i.e cementation, and subsequent heat treatment. The components must be quenched after carbon saturation itself to obtain a hard surface layer and a tough core, and subsequently lowered to lower the residual austenite to reduce internal stresses. In the experiment, the gears of the same pitch, with the same chemical composition and processing, were cemented to three given depths of cementation. Subsequently, carbon saturation calculations were made using carbon under different time conditions. To demonstrate the influence of temperature on the cementing process, an experiment was carried out at the conclusion of the diploma thesis, where the temperature of cementation was reduced and the effects of this change on the other parameters of the process were examined. In addition to the unique input quantities, the so-called carbon-to-carbon transfer coefficient β_C has to be taken into account for a more precise calculation of diffusion. This coefficient affects the thickness of the diffusion layer at the interface of the metal atmosphere resulting from the heat transfer, and defines the amount of carbon atoms that receives the surface of the steel from the atmosphere [Hazlinger 2013].

2 CHARACTERIZATION OF CARBON DIFFUSION IN METALS

The mechanism of carbon diffusion in metals is based on the introduction/movement of carbon atomsin the crystalline metal lattice.

The diffused carbon atoms settle into the position between the atoms of the crystalline iron grid. The rate of diffusion is governed by Fick's laws. The rate of diffusion of carbon is the efficacy coefficient of D_C.

The penetration of the atom of another element into the crystalline lattice of the metal depends primarily on the dimensions of its crystalline lattice and the dimension of the atom of the penetrating element. An example is diffusion of carbon and nitrogen in the iron, respectively in the steel. The size of radius of the carbon atom is $0.77 \cdot 10^{-10}$ [m] and the iron radius size is$1.28 \cdot 10^{-10}$ [m]. To solve carbon diffusion in metals, the Arrhenian´s equation, which can be applied to determine the rate of diffusion of carbon atoms in connection with activation energy and diffusion conditions, is important. As the increasing activation energy decreases, the rate of diffusion occurs. Rising temperature increases the mobility of carbon atoms - increases carbon diffusion, [Pisek 1974], [Brandes 1992], [Totten 2006].

$$D_C = D_{0C} \cdot e^{-\frac{\Delta H_D}{RT}} , \qquad (1)$$

Where: D_C - diffusion coefficient of carbon atoms $[m^2 \cdot s^{-1}]$,D_{0C} - frequency factor of diffusion of carbon atoms $[m^2 \cdot s^{-1}]$,ΔH_D - carbon diffusion activation energy $[J \cdot mol^{-1}]$,R - gas constant 8 314 $[J \cdot kmol^{-1} \cdot K^{-1}]$,T - absolute temperature of the carbon diffusion process [K].

Tab. 1 shows the values of the diffusion coefficient of carbon in the iron of the different elements in iron and the values for its calculation.

The process of carbon diffusion in metals (e.g. inα-Fe, γ-Fe) can be described by two Fick laws, which are dependent on the carbon diffusion coefficient D outside the carbon atom diffusion conditions.

Application of 1st Fick's law for calculating carbon diffusion is determined for diffuser under constant conditions. This means that the concentration gradient $\partial c/\partial x$ does not change over time. The diffusing carbon atoms move in the direction of decreasing concentration. 1st Fick's law generally determines the diffusion flux of J atoms of the diffusing substance. Diffusion flow J is given by the number of atoms that pass through the unit area perpendicular to the direction of diffusion per unit of time. The diffusion flux J (for carbon diffusion J_C) is directly proportional to the diffusion coefficient D, resp. for D_C carbon diffusion [Machuta 2014], [Calister 2003].

$$J_C = -D_C \cdot \frac{\partial c_C(x)}{\partial x} , \qquad (2a)$$

$$\beta_C(c_P - c_S) = -D_C \cdot \frac{\partial c_C(x)}{\partial x} \qquad (2b)$$

Where: J_C - diffusion flow of carbon atoms $[kg \cdot m^{-2} \cdot s^{-1}]$,
D_C - carbon diffusion coefficient $[m^2 \cdot s^{-1}]$,
c_C (x) - the concentration of the diffusing element at the location x,
x - instead of the observed carbon diffusion,
β_C – the carbonsharing factor $[m \cdot s^{-1}]$,
C_P - concentration of the carbon saturation atmosphere [wt. %C]
C_S - carbon concentration on the surface of the carburized material [wt. % C]
$\partial c_C(x)/\partial x$- a gradient of the carbon atom at the location x.

Fig. 1 shows a carbon transfer mechanism during carburizing of the material. The basic parameters of this process are: the carbon (mass) coefficient β_C defining the flow of carbon atoms from the atmosphere to the surface of the steel and the carbon diffusion coefficient in the D_C steel at austenitic temperatures.

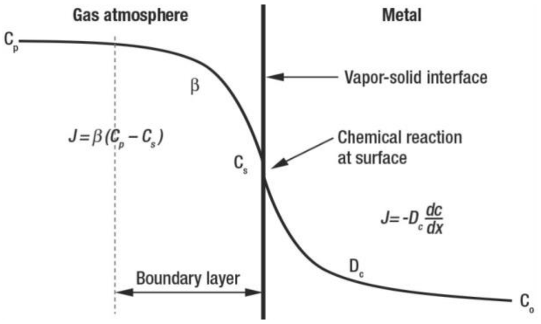

Figure 1. Schematic representation of carbon transport in carburization proces [Dulcy 1999], [Karabelchtchikova 2007]

Due to the process kinetics, the maximum carburettage rate is reached when carbon transfer from the atmosphere is equal to or greater than the solid state carbon diffusion rate. Such a diffusion-controlled process has no carbon deficiency fed to the interface for its further transport to the solid; a constant surface carbon content can be assumed. In practice, however, the transformation of the non-equilibrium carbon from the atmosphere into the solids boundary, including the surface reaction often referred to as the speed limiting factor [Dulcy 1999], [Stolar 1984], especially at the beginning of the carburettage process. Although the carbon transport mechanism is well known, experimental results have shown[Stolar 1984], [Karabelchtchikova 2007], [Karabelchtchikova 2006] that for different carbonaceous atmospheres, carbon concentration curves often deviate from those predicted. This suggests that knowledge of carbon potential and carburizing time is not sufficient for process control and that β and D require attention [Karabelchtchikova 2006], [Batz 1950]. These coefficients are important parameters of carbon diffusion processes for successful control of (2b) the gas carburization process [Karabelchtchikova 2006]. The diffusion coefficient D_C indicates the number of moles of a given component that passes the unit area per unit of time at the unit gradient of the component concentration – then carbon concentration.The partial derivative symbol indicates that concentration is variable not only in space but also in time [Karabelchtchikova 2007]. Carburization occurs when the value of carbon activity in the atmosphere is greater than that of carbon in the steel. Then, the diffusion carbon flow can be defined by the equation (2c).

Where: a_C^g - the carbon activity in the carbonaceous atmosphere;
a_C^s - the carbon activity in the steel before its carburizing;
k - velocity constant.

Diffusion Element	Diffusion Surrounding	D_{0C} $[m^2 \cdot s^{-1}]$	Action Energy ΔH_D $[kJ \cdot mol^{-1}]$	Calculate Values		References
				Temperature [°C]	D_C $[m^2 \cdot s^{-1}]$	
Carbon	α - Fe (BCC)	$2.0 \cdot 10^{-6}$	84.1	20 - 850	-	[Pisek 1974]
		$6.2 \cdot 10^{-7}$	80.0	500 900	$2.4 \cdot 10^{-12}$ $1.7 \cdot 10^{-10}$	[Brandes 1992]
Carbon	γ - Fe (FCC)	$4.0 \cdot 10^{-5}$	140.0	500 - 1000	-	[Pisek 1974]
		$2.3 \cdot 10^{-5}$	148.0	900 1100	$5.9 \cdot 10^{-12}$ $5.3 \cdot 10^{-11}$	[Brandes 1992]

Table 1. The tabulation of diffusion carbon data [Pisek 1974], [Brandes 1992]

$$J_C = \frac{dm}{dt} = k \cdot (a_C{}^g - a_C{}^s) = \beta_C \cdot (c_C{}^g - c_C{}^s) = \beta_C \cdot (c_P - c_S) \qquad (2c)$$

To describe the diffusion under real condition i.e, for example, under cementation conditions, it is important the 2nd Fick's law that addresses diffusion under non-stationary conditions. The rate of change of carbon concentration at the given location due to carbon diffusion is proportional to the change in the carbon concentration gradient at this point. For the calculation of carbon diffusion, the following equation can be used:

$$\frac{\partial c_C}{\partial t} = D_C \cdot \frac{\partial^2 c_C}{\partial x^2} \qquad (3)$$

Where: c_C - the concentration of diffusing carbon at a particular material site [wt. % C],
x - coordinate diffusion coordinates,
D_C - carbon diffusion coefficient $[m^2 \cdot s^{-1}]$,
t - time of carbon diffusion [s].

For solving the equation (3), it is possible to use for a soothing atmosphere - metal, resp. the semi-final environment ($0 < x < \infty$) to write the equation (4), that includes Gaussian integral of errors. The initial and boundary conditions apply to solving the equation (3). The initial pre-diffusion condition: for time = 0 (t = 0) is the initial concentration of C_0 v at each location $x > 0$. The boundary condition at the site of the carbonaceous atmosphere and material, $x = 0$, a constant C_S concentration is maintained for time $t > 0$.

$$\frac{C_{(x,t)} - C_0}{C_S - C_0} = 1 - erf\left[\frac{x}{2\sqrt{D_C \cdot t}}\right] \qquad (4a)$$

$$\frac{C_S - C_{(x,t)}}{C_S - C_0} = erf\left[\frac{x}{2\sqrt{D_C \cdot t}}\right] \qquad (4b)$$

Where: C (x, t) -concentration of the steel in a certain location x,
C_0 - initial carbon concentration in steel [wt. %],
Cs - carbon concentration at atmospheric-steel contact [wt. %],,
x - instead of the observed diffusing carbon concentration,
D_C - carbon diffusion coefficient $[m^2 \cdot s^{-1}]$,
t - time of carbon diffusion [s].

Due to the fact that during the carbon transmission rise at the interface atmosphere-steela diffusion boundary layer, the so-called carbon shift transfer coefficient β_C is considered for a more precise calculation of diffusion carbon. This coefficient defines the flow of carbon atoms from the atmosphere to the surface of the steel and involves the transfer of carbon through a layer of gas near the surface of the steel and the surface reaction kinetics [Hazlinger 2013], [Karabelchtchikova 2006], [Vodickova 2017], [Askenland 2003],[Mehrer 2007]. The x value for equations (4a) and (4b) can be calculated from:

$$x = h + \frac{D_C}{\beta_C} \qquad (5)$$

Where: x - instead of the observed diffusing carbon concentration,
D_C- carbon diffusion coefficient $[m^2 \cdot s^{-1}]$,
β_C - carbon-sharing factor $[m \cdot s^{-1}]$.

The D_C/β_C ratio determines the thickness of the diffusion boundary layer at the interface of the atmosphere and the carburized surface. In essence, the carbon atoms that pass into the surface layer of steel according to equation (5). Fig. 2 shows the context between the temperature and the carbonaceous atmosphere with the ratio D/β during carburising in a gaseous carburising atmosphere. For the particular conditions of carburising in a gaseous medium, it is possible to determine D/β from Fig. 2 based on the knowledge of the carburising temperature and the atmospheric C_P to determine D/β concentration value and then calculate the value of the carbon-sharing coefficient β (resp. β_C).

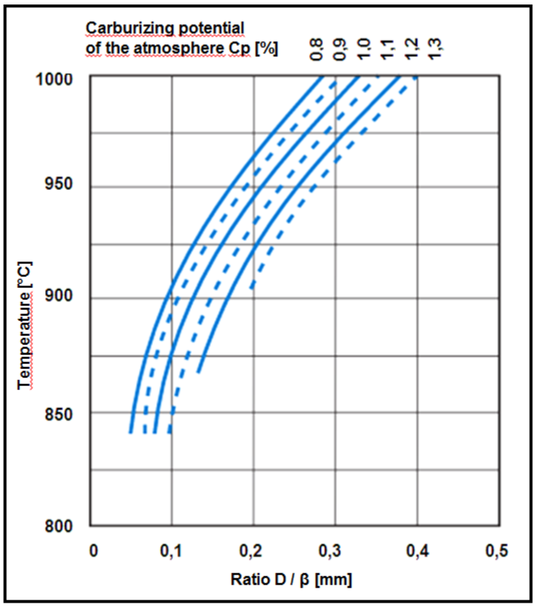

Figure 2. Values (D / β = D_C / β_C) for gas carburising [Hazlinger 2013]

Determination of the value of the carbon transfer coefficient β_C is made for a specific carburizing temperature [°C] and the carbonizing potential of the atmosphere cp [wt. % C]. For a carburizing temperature of 920 °C, the D_C/β_C ratio should be 0.2 [mm], i.e., $D_C/\beta_C = 2 \cdot 10^{-4}$ [m].

Based on the experimental research carried out by KRAUS [Kraus 2013], it was determined that the carbon concentration on the surface C_S of the carburized part was about 85 to 90% of the atmospheric abundant potential. Kraus [Kraus 2013] also indicates the relationship between the measured hardness of the cemented and hardened gears and the carbon content (e.g. on the surface of the gear wheels the surface was 740 HV, which corresponds to a hardness of 62 HRC and the carbon content is about 0.9%).

3 CALCULATION OF CARBON IN CEMENTED GEAR WHEELS

The computational part of this paper was focused on predicting of the amount of carbon in the steel gear wheels during their cementation. In technical practice, cementation is to be carried out in such a way that the minimum carbon content in the steel is 0.4 [wt. %]. For our experimental purposes, the carbon diffusion calculation was performed for a 0.6 mm, 0.8 mm, and 1.0 mm cement layer depth. At the same time it was assumed that the cementation temperature would be 950 ° C and the carbonaceous gas atmosphere Cp = 1. 2% C. Three practical cementation times (135, 210 and 300 minutes) were proposed based on practical experience with the cementation process.

According to the equation (1) the value D_{920} was calculated, using the diagram in Fig. 2, a ratio D_{920}/β_C was determined, the β_C value was determined and based on the practical experience with steel ČSN 14 220, the value of the initial carbon content in steel C_0 = 0.19 [%]. The calculated values D_{920}, D_{920}/β_C, β_C a C_0aregiven in Tab. 2.

According to equation (4a), the calculated carbon concentration $c_{(x,\ t)}$ was determined by the distance from the surface of the gearwheel. For calculation, the values in Tab. 2. were used. In both cases, carbon concentrations were calculated for 0.6 mm, 0.8 mm, and 1.0 mm cement layer depths. Calculated values were plotted, see Fig. 3.

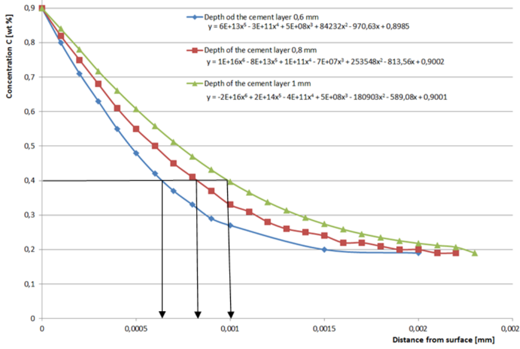

Figure 3. Concentrationofcarbon in surface are as of cemented gear wheels
C_P =1.2 wt. %C,$D_C = 2.97 \cdot 10^{-11}$ [m²·s] a $\beta_C = 1.49 \cdot 10^{-7}$ [m·s];

4 EXPERIMENTAL CEMENTATION OF GEAR WHEELS

In the experiment, cementation of gears was performed. The wheels were made of low alloyed Mn-Cr structural steel ČSN 14 220 used for cementation. Tab. 3 shows the chemical composition of the steel. The content of the elements corresponds to the prescribed range.

Depth of carburizing [mm]	Carburizing time [s]	D_{920} [$m^2 \cdot s^{-1}$]	D_{920}/β [m]	β [$m \cdot s^{-1}$]	C_0 [%]
0.6	8,100	$2.97 \cdot 10^{11}$	$2 \cdot 10^{-4}$	$1.49 \cdot 10^{-7}$	0.19
0.8	12,600	$2.97 \cdot 10^{11}$	$2 \cdot 10^{-4}$	$1.49 \cdot 10^{-7}$	0.19
1.0	18,000	$2.97 \cdot 10^{11}$	$2 \cdot 10^{-4}$	$1.49 \cdot 10^{-7}$	0.19

Table 2. The values of the D_{920}, D_{920}/β_C, β_C and C_0

Chemicalcompositionsteel [wt. %]according to (ČSN 14 220)							
	C	***Si***	***Mn***	***P***	***S***	***Cr***	***Al***
Prescribed	0.14 – 0.22	0.12	1.0 – 1.5	0.035	0.020-0.035	0.8 -1.3	0.014-0.040
Contained	0.19	0.11	1.35	0.010	0.02	1.18	0.03

Tab. 3. Chemical composition according to Czech standard CSN 14 220

The carburizing was carried out by automatically controlled Monocarb furnace at 920 °C (1193 K). Three different thicknesses of the cementitious layers of 0.6 mm, 0.8 mm and 1.0 mm were made on these wheels, see Fig. 4. The initial carbon content in the gear steel was c0 = 0.19% C. The cementitious atmosphere was a mixture of methanol and propane. Cementing potential of carbonizing atmosphere c_P = 1.2% carbon. The cementation time for each layer was different. For the cement layer of 0.6 mm, the cementation time was 8,100 s, for the 0.8 mm layer the cementing time was 12,600 and for the 1,0 mm layer the cementation time was 18,000 s. After the cementation, the wheels were cooled to 720 °C. It was then heated to a hardening temperature of 830 °C and subsequently cooled in 80 °C oil. After hardening in oil, the low temperature tempering process was followed at 170 °C for 120 minutes. In Fig. 4, are the wheels ∅ 76 mm.

Figure 4. The carburizing **gear wheels**of steel by CSN 14020

According to the CSN 42 0003 standard, the microstructure of the steel for the production of gears was evaluated. The structure exhibited ferrite and lamellar perlite. In addition, according to CSN 42 0469, linearity was assessed. Steel for the production of gears showed no significant linearity [Karabelchtchikova 2007].

Metalographic analysis of cementation layer and steel gear structure

The accuracy of the theoretical calculations of carbon diffusion during cementation of gears was based on the metallographic evaluation of the respective diffusion layers of samples of cement wheels. For this purpose, metallographic observations were made. A light microscope was used as a tool for this. After the cementation for metallographic observation, the gear wheel samples were prepared by conventional metallographic method (grinding, polishing and etching). Metallographic samples included a cutout of the gear wheel including 4 teeth. This cutout was cut once more perpendicular to the teeth. The samples were pressed into metallographic resin (Isofast and Multifast). The samples were then ground and polished on the Struers Tegrapol-35 metalographic polisher. Polishing agent for diamond suspensions and diamond slurry with grains of 3 μm were used for polishing. The steel structure was etched using a 5% solution of nitric acid in ethanol.

The cementitious layer of the gearwheels was observed on a Neophot light microscope 21. In Fig. 5 there are two teeth of the wheel, the lighter parts of the teeth are a carburaising layer and the darker part is an unassembled area of the sprocket.

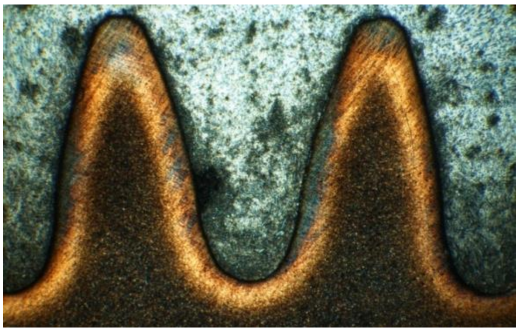

Figure 5. Carburizing layer 0.6 mm of the gear wheel, 10 x enlarged

The determination of the carburising layer of each tooth of the gear samples was performed on the Olympus GX500 microscope, where the thickness of the carburising layer of the gearwheels was measured. In all samples, the carburising layer was measured from six positions perpendicular to the tooth surface. In all three types of gear samples are the required cementation layers of 0.6 mm, 0.8 mm and 1.0 mm. Measured values of cement layers are given in Tab. 8. Fig. 6 shows the respective cementitious layers. At the same time, Tab. 4 lists the values of the statistical quantities (average value of the cement layer, standard deviation and coefficient of variation) which were calculated according to the following relations:

The arithmetic mean:

$$\bar{x} = \frac{1}{n} \cdot \sum_{i=1}^{n} x_i \qquad (6)$$

The standard deviation (SD, also represented by the Greek letter σ, or the Latin letter s):

$$s = \sqrt{\frac{1}{n-1} \cdot \sum_{i=1}^{n} (x_i - \bar{x})^2} \qquad (7)$$

The variation coefficient:

$$v = \frac{s}{\bar{x}} \qquad (8)$$

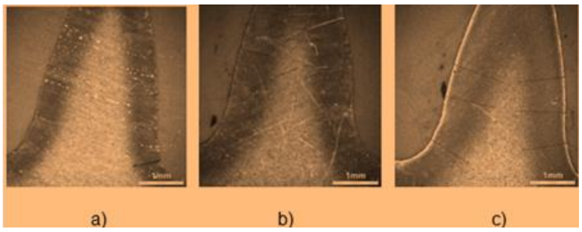

Figure 6. Carburizing layer of gear wheels, a) 0.6 mm; b) 0.8 mm; c) 1.0 mm

Carburizing layer [mm]	The measured thickness of the cement layer of the tooth						*s* *[mm]*	$\bar{x}$ *[mm]*	*v* [1]
	1	2	3	4	5	6			
0.6	0.66	0.65	0.62	0.61	0.61	0.60	**0.02**	**0.63**	**0.04**
0.8	0.83	0.81	0.82	0.83	0.79	0.80	**0.02**	**0.81**	**0.02**
1.0	0.98	0.91	0.95	0.92	0.95	0.96	**0.02**	**0.95**	**0.03**

Table 4. Values of carburising layer of gear wheels

a) Heat treatment of gears and microstructure of cemented and heat treated samples

After carburizing, the gearwheels were hardened in 80 °C oil by anisothermic austenitic breakdown for steel CSN 14 220 (Czech standard), see in Fig. 6.

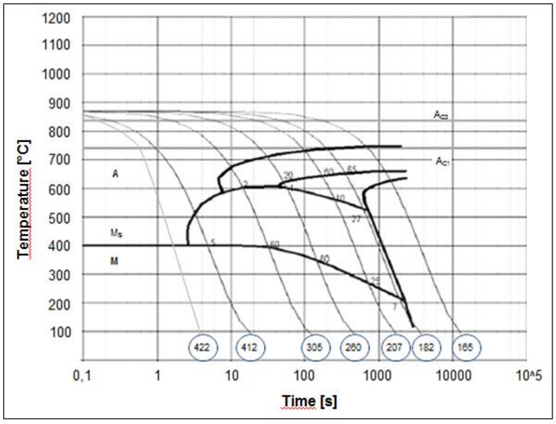

Figure 7. Austenitic anisotherm disintegration diagram for steel CSN 14 220 [CSN 14 220]

The martensitic structure was created by the quenching of the steel. This structure is hard, fragile and shows considerable strain. In order to reduce strain and therefore fragility, the gears were low-temperature lowered - heated to 170 ° C for 2 hours. In low temperature tempering, carbon martensite is discharged into the martensite needles as a non-equilibrium carbide ε ($Fe_{2,4}C$) with a tightly arranged hexagonal lattice. At this stage, martensite is referred to as low-carbon cubic martensite. Carbid is mainly precipitated at the borders of martensite and has a strong curing effect. Low temperature softening, however, will cause a slight decrease in hardness but also a significant decrease in fragility [Kraus 2013].

b) Verification of depth of carburised layer based on microhardness measurement of gear structure after hardening

To measure the microhardness of the teeth, the standard Vickers method was chosen. The measurement was carried out according to EN ISO 2639 - "Steel - Determination and verification of the depth of cementation". The depth of the cement layer, resp. the depth of cementation (CHD - Case Hardened Depth) is determined by a hardness of 550 HV. To measure microhardness, the LECO LM247AT microtest hardness was applied to the HV1 load, in accordance with the standard. Microhardness was measured at four points perpendicular to the edge of the tooth - from the tooth and tooth heights on both sides and also in the tooth core, see diamond regular quadrilateral pyramids on Fig. 8.

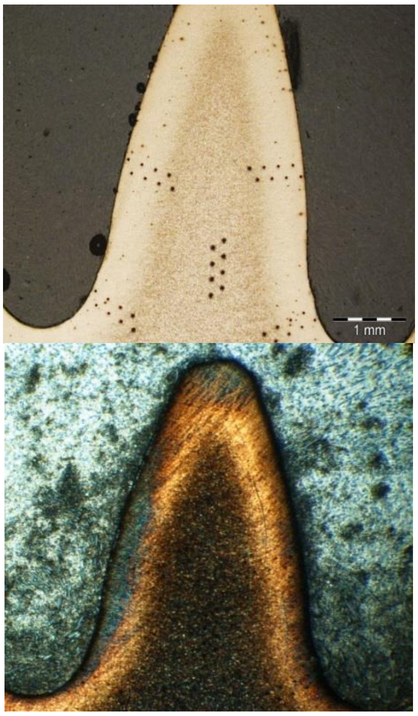

Figure 8. Example of measurement of microhardness on the teeth of wheels after carburisition

Tab. 5, Tab. 6 and Tab. 7 shows the results of the microhardness measurement of the analyzed metallographic samples depending on distance from the surface. These values are also shown graphically. Always on the last line of the table there is a depth of carburising at which the specified hardness limit of 550 HV is determined, determining the boundary of the carburising layer.

Values of the micro-hardness HV1 (carburizing layer 0.6 mm)					
Distance from the surface [mm]	**Tooth brush from the left (1)**	**Tooth brush from the right (2)**	**Bottom tooth from left (1)**	**Bottom tooth from right (2)**	**Cylindrical surface**
0.05	737	741	737	733	416
0.15	741	754	733	728	402
0.25	724	745	720	708	418
0.35	692	720	677	662	420
0.45	648	677	628	618	394
0.55	593	621	547	541	414
0.65	531	552	503	499	416
0.75	494	503	447	457	413
Value CHD 550 [mm]	**0.62**	**0.65**	**0.55**	**0.54**	**Out of range**

Table 5. Thickness depth of carburising 0.6 mm - Microhardness measurement

Values of the micro-hardness HV1 (carburizing layer 0.8 mm)					
Distance from the surface [mm]	**Tooth brush from the left (1)**	**Tooth brush from the right (2)**	**Bottom tooth from left (1)**	**Bottom tooth from right (2)**	**Cylindrical surface**
0.05	712	733	724	741	360
0.15	772	772	763	763	369
0.25	767	771	767	753	375
0.35	772	767	737	750	373
0.45	745	750	728	724	375
0.55	733	724	692	689	373
0.65	696	689	645	655	375
0.75	692	645	593	599	366
0.85	652	593	544	536	364
0.95	596	547	511	511	364
1.05	508	513	459	467	-
1.15	492	499	431	439	-
1.25	465	474	427	402	-
Value CHD 550 [mm]	**0.95**	**0.94**	**0.84**	**0.83**	**Out of range**

Table 6. Thickness depth of carburising 0.8 mm - Microhardness measurement

Values of the micro-hardness HV1 (carburizing layer 1.0 mm)					
Distance from the surface [mm]	**Tooth brush from the left (1)**	**Tooth brush from the right (2)**	**Bottom tooth from left (1)**	**Bottom tooth from right (2)**	**Cylindrical surface**
0.05	736	741	737	733	457
0.15	742	754	733	728	460
0.25	724	745	720	708	449
0.35	697	699	682	672	465
0.45	670	672	658	652	440
0.55	662	652	624	621	447
0.65	635	635	596	587	430
0.75	615	605	570	569	425
0.85	587	587	553	548	-
0.95	550	555	492	499	-
1.05	544	541	476	465	-
1.15	523	536	445	443	-
1.25	503	520	410	420	-
ValueCHD 550 [mm]	**0.95**	**0.94**	**0.84**	**0.83**	**Out of range**

Table 7. Thickness depth of carburising 1.0 mm - Microhardness measurement

The Fig. 9, 10 and 11 illustrate the graphical dependence of the hardness on the distance from the surface of the gear. Case Hardened Depth (CHD) is defined as the depth from the surface to the point where the hardnessis 550HV according to European Standards.

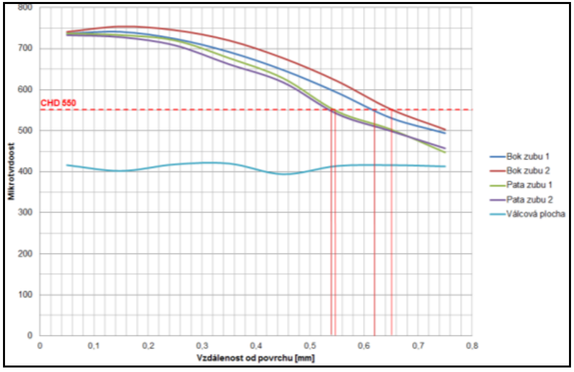

Figure 9. Determination of the Case Hardened Depth (CHD) of carburising (0.6 mm) according to microhardness

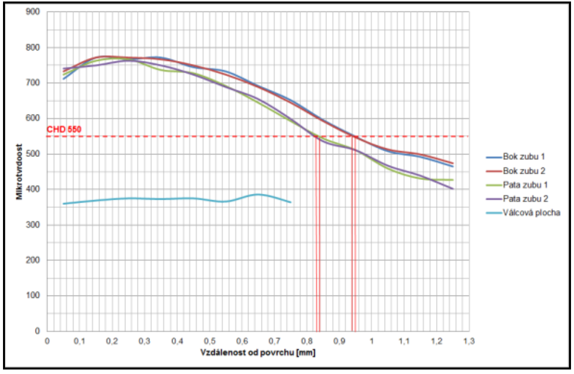

Figure 10. Determination of the Case Hardened Depth (CHD) of carburising (0.8 mm) according to microhardness

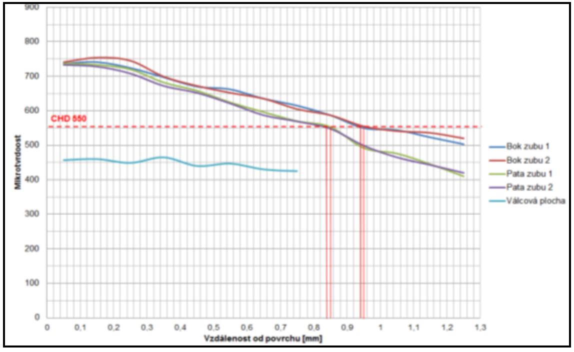

Figure 11. Determination of the Case Hardened Depth (CHD) of carburising (1.0 mm) according to microhardness

After calculating of the arithmetic mean of the depth values of the cementitious layer, the value of the carbirizing layer 0.59 mm was determined at the required depth of 0.6 mm. At the required depth of 0.8 mm, its average value was 0.89 mm, a deviation of 10% from the target value. At the desired 1.0 mm carburizsing layer, the average thickness of the cementitious layer was 0.96 mm, which is only 4% less than the target. In order to summarize the results of the microhardness measurement according to CSN EN ISO 2639 it can be stated that the deviation of the dimensions of the individual carbirizing layers was 2 to 10% of the required depth of the cemented layer.

c) Microstructure of cemented and heat treated specimens of gears

For microscope specimens the microstructure was evaluated after heat treatment. For this purpose, the Olympus GX71 microscope was used. Fig. 8 (on the right) is a tooth microstructure with a 0.6 mm thick cement layer thickness. The image can distinguish the lighter - coated layer and the darker core of the tooth. Fig. 8 (on theleft) is the impression of the microtest. After the measurement of the cement layer, the required depth of carburising depth of 0.6 mm can be confirmed. Fig. 12 shows a transition region from the cementitious layer to the core of the sample. The cement layer has a size of 0.6 mm. In Fig. 13 this area is 1000x enlarged. On the left, there is a martensitic structure that exhibits a high hardness, then going to the right in a structure consisting predominantly of a bainitic structure.

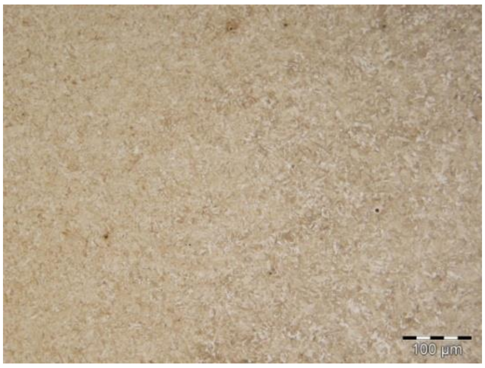

Figure 12. Transition area from the carburizing layer after hardening and tempering to the distant parts toward the core, martensite (left) and bainite (right), 200x magnified

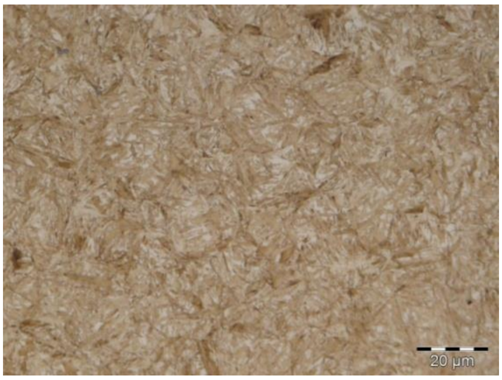

Figure 13. Microstructure of cement layer after hardening and tempering - martensite, residual austenite, 1000x magnified

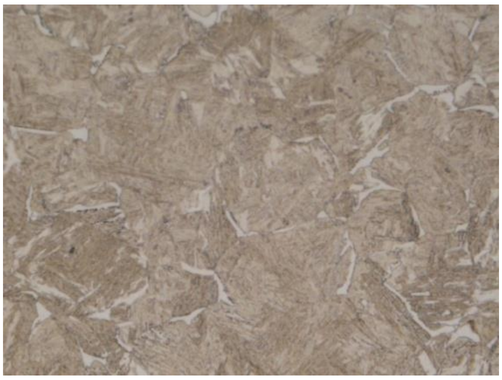

Figure 14. The microstructure of the transition region into the tooth core is formed by bainite and ferrite

5 CONCLUSION

For carburising of steels, in this case of gearwheels, is of the physical importance of carbon diffusion and the possibility of diffusion calculations. For calculating of diffusion processes, the Arrhenian equation and Fick's laws are important. To monitor diffusion on individual teeth of the wheel, it is possible to use relations for rectangularcoordinates. For these calculations, the appropriate physical quantities must be used. For these calculations, the value of the carbon diffusion $D_C = 2.97{\cdot}10^{-11}$ [$m^2{\cdot}s^{-1}$], corresponded to the carbon-sharing coefficient $\beta_C = 1.49^{-7}{\cdot}10^{-11}$ [$m{\cdot}s^{-1}$].The diffusion process increases the amount of carbon in the steel, at least up to 0.4 [wt % C]. This steel can then be heat-treated and de-energized in an efficient way. This paper shows the interdependence of the theoretical calculations of carbon diffusion during carburising of steel gear wheels with subsequent practical realization of cementation process with subsequent hardening and tempering. The diffusion calculation of carbon was aimed at obtaining three depths (diffusion distances from the surface) of 0.6 mm, 0.8 mm and 1.0 mm, where a concentration of 0.4% carbon was achieved. Thereafter, followed the carburising of gear wheels into three depths (0.6 mm, 0.8 mm and 1.0 mm). Subsequently, the gears were hardened and tempered.

On the basis of the solution made it is possible to formulate the following partial conclusions regarding the carbon diffusion:

1) Using a carbonaceous atmosphere having a cP content of 1.2% C and a cementation temperature of 920 ° C,according to the diffusion calculation on the surface of the cemented wheel, the carbon concentration is 0.95%. By diffraction calculation, a carbon concentration of 0.42% was achieved at a cementitious layer of 0.6 mm at a curing temperature of 920 ° C in 135 minutes (8,100 s). In the diffusion calculation of the 0.8 mm cement layer, a carbon concentration of 0.41% was determined at a temperature of 920 ° C with diffusion lasting 210 minutes (12,600 s). In the diffusion calculation of the 1.0 mm thick cement layer, the carbon concentration was 0.40% formed by diffusion lasting 300 minutes (18,000 s).

2) Measurement of the hardness of the teeth of wheels after cementation and subsequent hardening with tempering is a relatively good method for determining the depth of carbon diffusion, resp. cementation. As is well known, it has also been confirmed that a Vickers method is suitable for this purpose, which is carried out on the relevant metallographic sample. The determination and verification of the depth of cementation wasdone by the CHD - Case Hardened Depth. It is determined by a hardness limit of CHD 550. The values of microhardness range from 741 to 550 HV1. By calculating the arithmetic average of hardness, the depths of cementation layers were as follows. For 0.6 mm (0.59 mm depth) for 0.8 mm (found depth 0.89 mm) and 1 mm (0.96 mm depth).

3) By tracking the structure of cemented and heat-treated gears it was confirmed that by carburizing and hardening a martensitic structure with a certain amount of residual austenite was obtained in the surface layers. The transition region from the cementation to the core of the tooth of the wheel is made of martensite and bainite. The microstructure of the tooth core from the surface is formed by bainite and ferrite.

4) Practical use of carbon diffusion during cementation is the question of how to increase the diffusion rate.One possibility is to increase the difference of c_C^g-c_C^s (Cp-Cs), resp. a_C^g - a_C^s. Austenite carbon activity is determined by choosing the type of cementation steel. It can not be affected by cementation, but it is possible to increase carbon activity in the atmosphere. The highest value a_C^g = 1 is the limit value. At the activity value a_C^g = 1, there are the soots precipitation on the steel surface. Another limitation is the mass flow of carbon. This value must not cause the carbon saturation limit in austenite to be exceeded at the surface of the steel (carbides would result). In practice, so-called two-phase cementation is often used, whereby the first stage results in a maximum saturation rate and a maximum austenite carbon content is reached quickly.

In the second phase, the carbon potential is reduced and the austenite carbon diffusion decreases the gradient dc/dx at the expense of the maximum carbon content directly at the surface. Another possibility to increase the surface accelerating rate is to increase the value of carbon-sharing coefficient β_C and to increase the value of the D_C (coefficient of carbon diffusion). The carbon-sharing factor $\beta_C$is mainly dependent on the composition of the carbonaceous atmosphere. The D_C diffusion coefficient increases exponentially with the temperature. Therefore, the increase in cementation temperature shortens the cementation time. The effect of too high temperature on cementation results in the roughness of the austenitic grain of the carburizing component. This degrades the mechanical properties of the steel after carburization.

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