# STUDY OF THE CARBURIZATION OF A HYPOEUTECTOID STEEL (~0.20% C) AND ITS INFLUENCE ON MICROSTRUCTURE

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**Abstract**: *The paper presents the study of the diffusion phenomenon in metallic materials and its application in the carburizing process of hypoeutectoid steels. The fundamental mechanisms of atomic diffusion are analyzed, namely vacancy diffusion and interstitial diffusion, as well as the influence of temperature on atomic mobility. Based on Fick's second law, non-steady-state diffusion is addressed, establishing the relationship between concentration, time, and the penetration depth of the diffusing element.*

*The theoretical study is complemented by a calculation example of the time required for carburizing a steel with 0.25% C, in order to obtain a carbon concentration of 0.80% at a depth of 0.5 mm, at a temperature of 950°C. The obtained result indicates a treatment time of approximately 7 hours.*

*In the experimental part, carburizing of a C22 steel in a methane atmosphere was carried out, followed by metallographic analysis. The microstructure shows the formation of a carburized surface layer consisting of high-carbon martensite, a transition zone with a mixed structure, and a ferrite-pearlite core. The high hardness of the surface layer confirms the effectiveness of the treatment.*

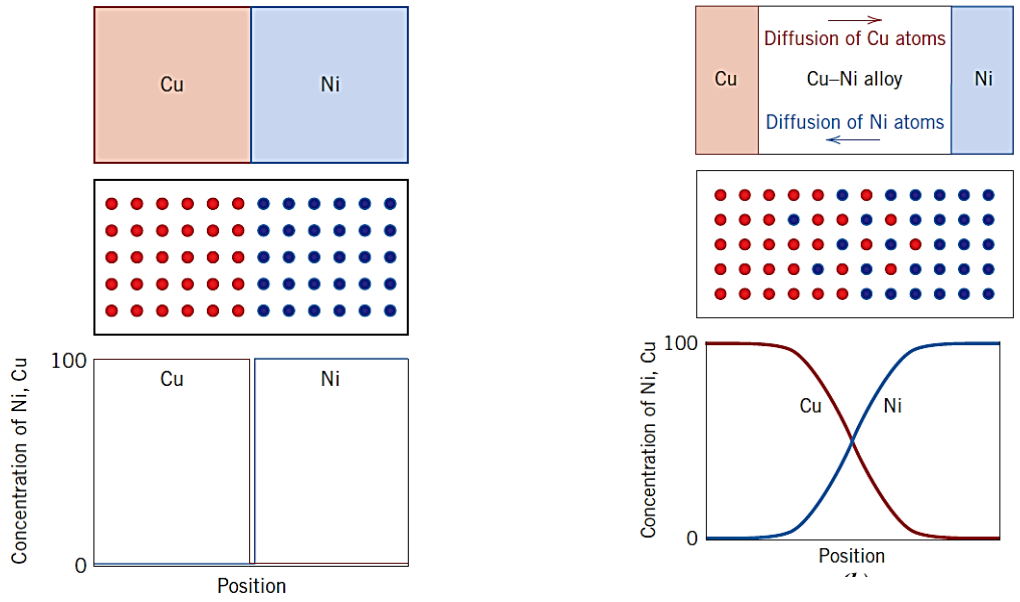
*The results demonstrate that the carburizing process enables an optimal balance between surface hardness and core toughness.*

**Key words:** carburizing, diffusing, Fick law, martensite, hardness

## 1. INTRODUCTION

Many important reactions and processes in materials treatment are based on mass transfer either within a specific solid (usually at the microscopic level) or from a liquid, gas, or another solid phase. This transfer necessarily occurs through diffusion, the phenomenon of matter transport via atomic motion. This chapter discusses the atomic mechanisms by which diffusion occurs, the mathematics of diffusion, and the influence of temperature and diffusing species on the diffusion rate.

The diffusion phenomenon can be demonstrated using a diffusion couple, formed by joining two bars of different metals in such a way that there is intimate contact between the two surfaces; this is illustrated for copper and nickel in fig.1.a, which includes schematic representations of atomic positions and composition along the interface. This couple is heated for a long period at a high temperature (but below the melting temperature of both metals) and then cooled to room temperature. Chemical analysis reveals a situation similar to that shown in fig.1.b - namely, pure copper and pure nickel at the two ends of the couple, separated by an alloyed region. The concentrations of both metals vary with position, as shown in fig.1.b (bottom). This result indicates that copper atoms have migrated or diffused into nickel, and that nickel has diffused into copper. The process by which atoms of one metal diffuse into another metal is called interdiffusion or impurity diffusion. [1]




a b

**Fig.1**. Comparison of a copper–nickel diffusion couple (a) before and (b) after a high-temperature heat treatment. The three diagrams for both parts (a) and (b) represent the following: top — the nature of the diffusion couple; middle — schematic representations of the atomic positions of Cu (red circles) and Ni (blue circles) within the couple; bottom — the concentrations of copper and nickel as a function of position along the couple.

Interdiffusion can be observed from a macroscopic perspective through the changes in concentration that occur over time, as seen in the example of the Cu–Ni diffusion couple. There is a net flux or transport of atoms from regions of high concentration to regions of low concentration. Diffusion also occurs in pure metals, but all atoms that change positions are of the same type; this phenomenon is called self-diffusion. Of course, self-diffusion cannot normally be observed through changes in composition. [1]

## 2. DIFFUSION MECHANISM

From an atomic perspective, diffusion simply represents the gradual migration of atoms from one lattice site to another. In fact, atoms in solid materials are in continuous motion, rapidly changing positions. For an atom to undergo such a displacement, two conditions must be met: there must be an adjacent vacant site, and the atom must have sufficient energy to break bonds with neighboring atoms and to produce a certain distortion of the lattice during its movement. This energy is of vibrational nature. At a given temperature, a small fraction of the total number of atoms is capable of diffusive motion due to their vibrational energy levels. This fraction increases as temperature rises. Several models have been proposed for this atomic motion; among them, two are predominant for diffusion in metals.

### Vacancy diffusion

One mechanism involves the exchange of an atom from a normal lattice position with an adjacent vacant lattice site (a vacancy), as schematically represented in fig.2.a This mechanism is appropriately called vacancy diffusion. Naturally, this process requires the

presence of vacancies, and the extent to which vacancy diffusion can occur depends on the number of these defects; significant vacancy concentrations can exist in metals at high temperatures. Since both the diffusing atoms and the vacancies exchange positions, atomic diffusion in one direction corresponds to vacancy movement in the opposite direction. Both self-diffusion and interdiffusion occur via this mechanism; for the latter, impurity atoms must substitute for host atoms. [1]

**Interstitial diffusion**

The second type of diffusion involves atoms migrating from one interstitial position to an adjacent vacant one. This mechanism occurs in the case of interdiffusion of impurities such as hydrogen, carbon, nitrogen, and oxygen, whose atoms are small enough to fit into interstitial sites. Host atoms or substitutional impurities rarely occupy such interstitial positions and normally do not diffuse by this mechanism. This phenomenon is appropriately called interstitial diffusion (fig. 2.b). In most metallic alloys, interstitial diffusion occurs much more rapidly than vacancy diffusion, because interstitial atoms are smaller and therefore more mobile. In addition, there are more available interstitial positions than vacancies; thus, the probability of motion of interstitial atoms is higher than in the case of vacancy diffusion. [1,2]

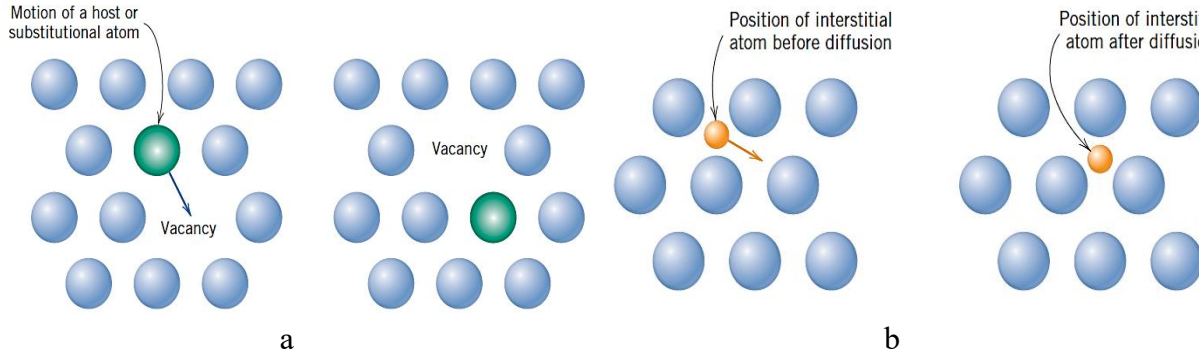



**Fig.2.** Schematic representations of (a) vacancy diffusion and (b) interstitial diffusion.

**Fick's Second Law — non-steady-state (transient) diffusion**

Most practical diffusion situations are non-steady-state—that is, the diffusion flux and the concentration gradient at a given point in a solid vary with time, leading to a net accumulation or depletion of the diffusing species. This is shown in Figure 3, which presents concentration profiles at three different diffusion times. Under non-steady-state conditions, it is possible to use Fick's first law, but it is not convenient; instead, a partial differential equation is used.

$$\frac{\partial C}{\partial t} = \frac{\partial}{x}\left(D\,\frac{\partial C}{\partial x}\right) \quad (1)$$

where C is the concentration in diffusion. [1,3]

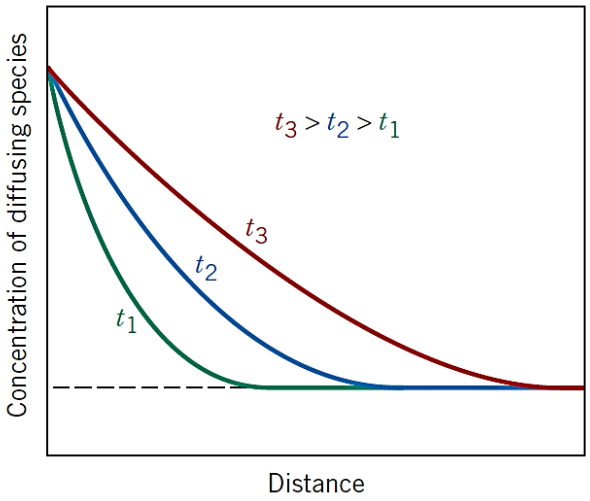



**Fig.3.** Concentration profiles for diffusion in a non-steady (transient) state, obtained at three different time moments, $t_1$, $t_2$ și $t_3$.

If the diffusion coefficient is independent of composition (which must be verified for each particular diffusion case), Equation (1) reduces to:

$$\frac{\partial C}{\partial t} = \left(D \frac{\partial^2 C}{\partial x^2}\right) \qquad (2)$$

Often, the source of the diffusing species is a gas phase whose partial pressure is maintained at a constant value. In addition, the following assumptions are made:

1 - Before diffusion, the solute atoms diffusing in the solid are uniformly distributed, having the concentration $C_0$.

2 - The value of x at the surface is zero and increases with distance into the interior of the solid.

3 - Time is considered zero at the moment immediately preceding the start of the diffusion process.

These conditions are expressed simply as:

Initial condition:

- for $t = 0$ şi $C = C_0$, $0 < x < \infty$

Bounfary condition:

- for $t > 0$, $C = C_s$ (the constant surface concentration) la $x = 0$.
- for $t > 0$, $C = C_0$ , $x = \infty$

Applying these conditions to Equation 2 leads to the solution:

$$\frac{C_x - C_0}{C_s - C_0} = 1 - erf\left(\frac{x}{2\sqrt{Dt}}\right) \qquad (3)$$

where $C_x$ represents the concentration at depth x after time t. The expression $erf\left(\frac{x}{2\sqrt{Dt}}\right)$ is the Gaussian error function, with its values being listed in mathematical tables for different values of $\frac{x}{2\sqrt{Dt}}$. The concentration parameters appearing in Equation 3 are shown in fig.4, a concentration profile corresponding to a specific moment in time.

Thus, Equation 3 highlights the relationship between concentration, position, and time — namely that $C_x$, being a function of the dimensionless parameter $\frac{x}{2\sqrt{Dt}}$, can be determined at any time and at any position, provided that the parameters $C_0$, Cs, and D are known. [1,4]

Let us assume that a specific solute concentration, $C_1$, is to be obtained in an alloy; in this case, the left-hand side of Equation 3 becomes:

$$\frac{C_x - C_0}{C_s - C_0} = const. \quad (4)$$

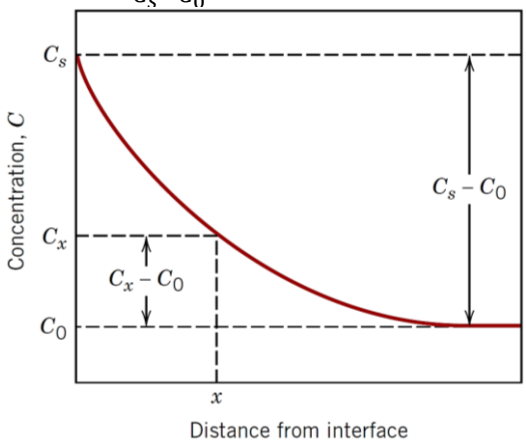



**Fig.3.** Concentration profile for transient (non-steady-state) diffusion

### 3. CASE STUDY

**Non-steady-state diffusion – time calculation**

For certain applications, it is necessary to harden the surface of a steel (or iron–carbon alloy) relative to its interior. One way this can be achieved is by increasing the carbon concentration at the surface, in a process called carburizing; the steel part is exposed at high temperature to an atmosphere rich in hydrocarbon gases, such as methane ($CH_4$).

Consider an alloy that initially has a uniform carbon concentration of 0.25 wt% and is to be treated at 950°C. If the surface carbon concentration is suddenly brought to and maintained at 1.20 wt%, how long will be required to obtain a carbon concentration of 0.80 wt% at a position located 0.5 mm below the surface?

The diffusion coefficient of carbon in iron at this temperature is $1.6 \times 10^{-11}$ m²/s; the steel piece is assumed to be a semi-infinite solid. Since this is a non-steady-state diffusion problem in which the surface composition is maintained constant, Equation 3 is used. The values of all parameters in this expression, except for the time t, are specified in the problem, as follows:

$C_0 = 0{,}25$ %C

$C_s = 1{,}20$ %C

$Cx = 0{,}80$ %C

$x = 0{,}50\text{mm} = 5 \times 10^{-4}\text{m}$

$D = 1{,}6 \times 10^{-11}$ m²/s

Therefore,

$$\frac{C_x - C_0}{C_s - C_0} = 1 - erf\left(\frac{x}{2\sqrt{Dt}}\right)$$

$$\frac{0,80-0,25}{1,20-0,25}=1-erf\left[\frac{(5\cdot 10^{-4})}{2\sqrt{1,6\cdot 10^{-11}\cdot t}}\right]$$

$$0,4210=erf\left(\frac{62,5s^{1/2}}{\sqrt{t}}\right)$$

We now need to determine the value of z for which the error function is 0.4210. Interpolation is required:

| z | erf(z) |
|---|---|
| 0,35 | 0,3794 |
| z | 0,4210 |
| 0,40 | 0,4284 |

so,

$$\frac{z-0,35}{0,40-0,35}=\frac{0,4210-0,3794}{0,4284-0,3794}$$

z = 0,392

Therefore,

$$\frac{62,5s^{1/2}}{\sqrt{t}}=0,392$$

t = 25400s = 7,1h

In order to apply the theory previously exemplified, through which we calculated the time required for carburizing a certain steel (7 hours), we also carried out a practical case study. Thus, we prepared a test sample that was subjected to a carburizing heat treatment under the conditions specified in the theoretical study: material – C22 steel, carburizing temperature – 950°C, carburizing atmosphere – methane ($CH_4$), and exposure time – 7 hours.

At the end of the heat treatment, a metallographic sample was prepared and examined using an optical metallographic microscope, resulting in the microstructure shown in fig. 4.

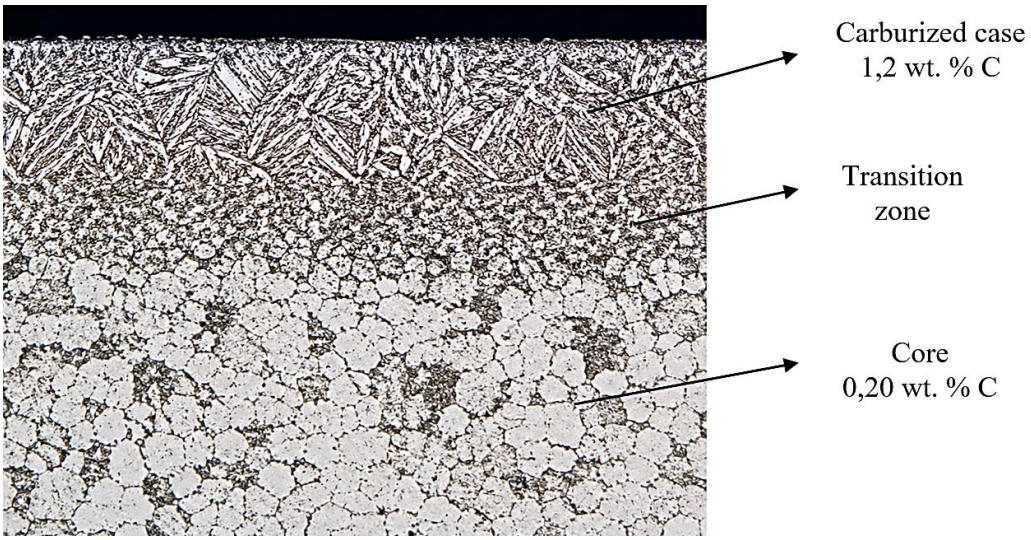



**Fig. 4** - Microstructure of the sample heat treated by carburizing

## 4. CONCLUSION

1 – Initial steel (0.22% C)

Hypoeutectoid steel – at room temperature, the initial microstructure consists of ferrite (white, equiaxed polygonal grains) and pearlite (dark-appearing islands). The ferrite/pearlite ratio in the figure confirms the carbon content of the steel.

2 – Carburizing heat treatment

Carburizing is a thermo-chemical treatment in which steel is held at high temperatures (900–960°C) in a carbon-rich atmosphere (in the present case – methane). Carbon atoms diffuse from the exterior toward the interior, with the concentration gradient decreasing from the surface to the core. After carburizing, the specimen was subjected to controlled cooling at a high cooling rate, in order to transform the carbon-rich structures into martensite, thus achieving high hardness in the surface layer.

3 – Microstructure after carburizing

In Figure 4, the regions characterizing the new structure obtained after heat treatment can be observed:

- Carburized case 1.2 wt.% C – in the upper layer, at a depth of approximately 0.3–0.5 mm, an acicular martensitic structure can be observed. The carbon concentration is approximately 1.1–1.2%. The hardness of the carburized surface was measured, with values of 56–58 HRC being obtained.
- Transition zone – beneath the carburized layer, the structure becomes finer and also more mixed: martensite combined with fine pearlite (small pearlite islands). The carbon concentration in the transition zone decreases to approximately 0.6–0.8 wt.% C.
- Core 0.20 wt.% C – beneath the transition layer, the initial structure is restored, consisting of ferrite and pearlite, characteristic of hypoeutectoid steels.

4 – Through carburizing, a hard and wear-resistant surface layer (high-carbon martensite) was obtained, while maintaining a tough and ductile core. In this way, a material was achieved that provides a combination of surface hardness and wear resistance, together with plasticity and mechanical strength in the bulk.

## 5. REFERENCES

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