

Analysis of the Kinetics of Hydrogen Absorption in Metals

Ludanov K.I., Bratanich T.I

Depart. N5, Institute for Renewable Energy of NASU
G. Hotkevicha str.,20A, Kiev, Ukraine, K. Ludanov.

The article is dedicated to my wife, Bratanich T. I., Dr. of Sciences (IPMS NASU), a famous scientist in the field of hydrogen storage in metals, the use of destructive hydration in materials science, as well as obtaining nanocomposites based on metal hydrides.

Abstract

The article developed analytical methods for calculating the parameters of the kinetics of hydrogen absorption by metals: a brief derivation of the process formulas is presented and methods for joint determination of the integral parameters of hydrogen absorption - the maximum specific hydrogen intensity, reduced diffusion resistance of the H₂ absorption process and estimation of the "activation time" of the surface based on a limited sample (2-3 points) experimental data. This method is implemented by solving systems of two transcendental equations, the coefficients of which are used in the experimental data on the process of hydrogen absorption by samples.

Keywords: hydrogen, metal, absorption kinetics, diffusion resistance, hydrogen consumption, induction period, activation energy.

I. INTRODUCTION

Almost all metals absorb hydrogen. In this case, some metals hydrogenate hydrogen (for example, Fe, Al, Mo, Pt), forming chemical compounds - hydrides. In other metals, hydrogen dissolves, forming solid solutions. The kinetics of hydrogen uptake by metals is mainly determined by the process of its diffusion in samples representing powders, compacts or plates. This is because the rate of chemical interaction, for example, hydrogenation, is much higher than the rate of diffusion of hydrogen in a metal sample. Therefore, the limiting factor in the absorption of H₂ by the metal is the diffusion resistance to the hydrogen flow on its way to the crystal lattice molecules.

II. OVERVIEW

For the first time, the phenomenon of hydrogen absorption by metals (in palladium, Pd) was established by the English scientist T. Gram (T. Gram, 1866). At present, metals are considered as a very promising material for the accumulation and

storage of hydrogen [1], since in this case it is practically explosion-proof.

It has long been established [2] and the sequence of diffusion propagation of hydrogen in metals. At first, H₂ gas molecules are adsorbed on a metal surface: more precisely, on its "active centers". On them, H₂ molecules dissociate into atoms, which then move under the action of a concentration gradient along the surface of the samples to the grain boundaries. Then atomic hydrogen diffuses "along the line of least resistance": it enters the samples along the grain boundaries, where the resistance to its motion is minimal, and only then the H atoms enter directly into the crystal grains through dislocations. And only then does the actual interaction of hydrogen atoms with crystal lattice molecules occur.

Two mechanisms of absorption of hydrogen by a metal are known [3]. Both of them begin with the adsorption of H₂ molecules of gaseous hydrogen on the surface of the sample (powder, compact or plate), or rather, on activated surface points (dissociation centers) and their subsequent dissociation into H atoms. Moreover, it is H atoms that diffuse into the metal sample. In the first case, hydrogen does not chemically react with the metal, but forms a solid solution. In other cases, a chemical reaction of hydrogen with metal molecules occurs, and its maximum hydrogen intensity is determined by hydrogenation stoichiometry (in accordance with the coefficients of the reaction formula).

If hydrogen does not react with the metal, it forms a solid solution with it. In this case, the maximum concentration of hydrogen in the metal is called solubility, the value of which at low pressures is determined by the Sieverts law [2]:

$$H_{\max} = k\sqrt{P_{H_2}},$$

where P_{H_2} – is the pressure of gaseous hydrogen above the surface of the sample.

For example, in [3] it was experimentally established that the rate of hydrogen absorption in Ti powder at a constant pressure of hydrogen in the chamber decreases exponentially with time:

$$V_t = V_0 \exp\left(-\frac{p}{c}t\right),$$

where p – is the gas pressure; c – is a constant; t – is the current process time. And the amount of hydrogen absorbed over time t is determined by the formula:

$$Q_t = V_0\theta \left[1 - \exp\left(-\frac{p}{c}t\right)\right]. \quad (1)$$

The total amount of hydrogen that can absorb the sample at pressure p is:

$$Q_{\max} = V_0\theta.$$

However, a mathematical conclusion and physical analysis of these dependences was not given in [3], and the mechanism of hydrogen absorption is also unclear.

In [4], the primary experimental data on the kinetics of hydrogen absorption by a metal sample in the coordinates “hydrogen capacity – time” (Fig. 1a) and preliminary processed experimental data in semilogarithmic coordinates are presented: along the ordinate axis is the logarithm of the free capacity of the sample for hydrogen saturation, along the abscissa axis – time (Fig. 1b). An analysis of the curves shows that if the stoichiometry of the reaction is known, i.e. H_{\max} can be calculated, the second form of presentation is much more informative, since it allows us to establish, in particular, that at the process time $t = 10$ min, the rate of saturation of the sample with hydrogen sharply changes. This is characterized by a “direct” kink due to changes in diffusion conditions. The rate of hydrogen saturation decreases, obviously, due to a sharp change in the structure of the sample as a result of a quick chemical reaction, at which the diffusion resistance of the hydrogen saturation process changes. Whereas in the graph (Fig. 1a), where the primary data are presented, this transition is very difficult to establish.

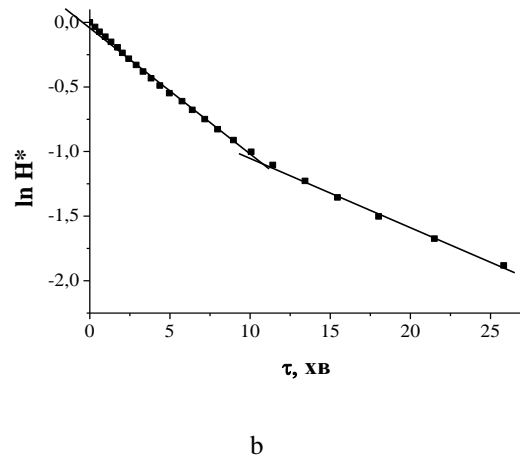
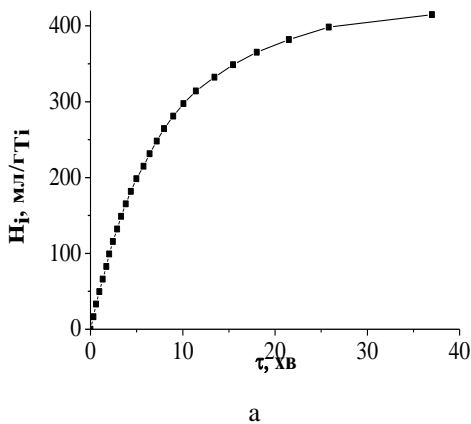


Fig. 1: Primary data in the coordinates “hydrogen intensity – time” (a) and recalculated data in the coordinates “lnH* – τ ” (b) of the diffusion rate during destructive hydrogenation (773 K, 1 MPa) of a pressed TiCu ingot.

Obviously, in the semi-logarithmic coordinates (Fig. 1b) it is quite easy to see the change in the hydrogen diffusion rate, moreover, in the figure it is very easy to establish the moment of structural transformation in the sample ($t = 10$ min). However, in cases where the maximum value of the hydrogen intensity of the sample is not known, it is impossible to present the experimental data in semilogarithmic coordinates. In addition, in the framework of the logarithmic model, it is impossible to analyze the case shown in Fig. 2 (curve 3) [6], in which there is a so-called incubation period (activation time) t_A of the sample surface ($t_A \neq 0$).

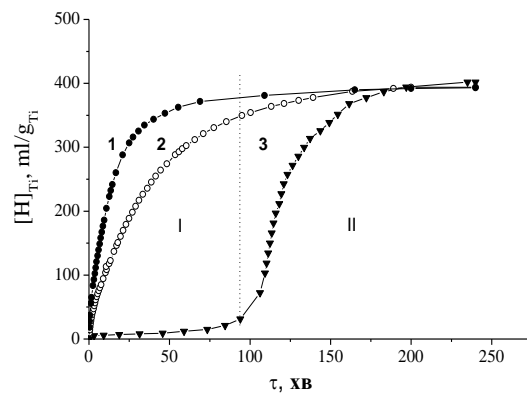


Fig. 2: The rate of absorption of hydrogen by titanium in the process of destructive hydrogenation of Ti_2Ni at temperature 773 K: 1 – pressed powder; 2 – pressed casting; 3 – plate.

III. FORMULATION OF THE PROBLEM

An analysis of the kinetics of hydrogen absorption by metals shows that this problem is quite relevant. That is, there is an urgent need to develop simple express methods for assessing process parameters: the diffusion resistance of the R_D process and the maximum hydrogen intensity of the C_H sample, which are combined into the so-called "time constant" T_0 : $T_0 = R_D C_H$. For this, firstly, it is necessary to formulate a rigorous mathematical model of the process of hydrogen absorption by metal. It is a priori obvious [3] that the kinetics model has an exponential form. Secondly, it is necessary to form the parameters of the exponential curve of the absorption kinetics. And thirdly, it is necessary to develop express methods for estimating the values of the parameters of the kinetic model based on a limited selection of experimental data.

For example, an analysis of the graph (Fig. 2) from [4] shows that the kinetic curve of hydrogen absorption by a metal can be written mathematically in a general way. Based on the analysis of the primary data on hydrogen absorption by metals (Fig. 2), the kinetic curve of the process in general can be written as follows:

$$H(t) = A(1 - e^{-t/T_0}), \quad (2)$$

where $H(t)$ – is the specific hydrogen intensity of the sample; t – is the current process time; T_0 – the "time constant" of the process, equal to: $T_0 = R_D C_H$; B – is a dimensionless quantity characterizing the activation time t_A of the sample surface.

Since the hydrogen flow in the metal overcomes a series of diffusion resistances, which are difficult to separate (if at all possible), the main task of this work is to formulate precisely generalized (integral) kinetic estimates: the reduced diffusion resistance of the R_D process. Indeed, R_D takes into account the diffusion coefficient D , the cross-sectional area of the hydrogen flux F , and the "penetration depth" of hydrogen atoms in the crystal lattice L . And the third unknown activation time t_A – is determined by the duration of the formation of "activation centers" on the sample surface. The activation time $t_A = T_0 \cdot B$ is determined by the duration of the process of formation of a sufficient number of "activation centers" on the surface of the sample.

IV. RESEARCH RESULTS

A. A brief derivation of the formulas for the kinetics of absorption of H_2 in metals.

The laws of diffusion were discovered by the German scientist Adolf Fick [3]. Fick's first law (1855) is written as follows:

$$j = -D \text{grad } c,$$

where j – is the flow of matter through the cross section F ; c is its concentration; D – is the diffusion coefficient. For the one-dimensional case, Fick's law has the form:

$$\frac{dm}{dt} = -D \frac{dc}{dx}.$$

If we go to the finite differences in the derivative $\frac{dc}{dx}$, then we can write: $\Delta c \sim \Delta H = H_{\max} - H(t)$, where $H(t)$ – is the average hydrogen consumption in the sample:

$$H(t) = V^{-1} \int H(x) dV$$

and $\Delta x \sim L$, where L – is the average depth of hydrogen penetration into the sample. If proportionality is used, where F is the effective cross-sectional area of the hydrogen flow, then in the differential equation obtained from Fick's first law, we can separate the variables:

$$\frac{dH}{H_{\max} - H(t)} = D \left(\frac{F}{L} \right) \cdot dt.$$

Integration of the resulting differential equation gives a formula similar to (1):

$$\delta H(t) = [H_{\max} - H(t)] / H_{\max} = \exp(-t/T_0) \quad (3)$$

Where $\delta H(t)$ – is the specific free hydrogen intensity of the sample, $\delta H(t) = H_{\max} - H(t)$.

In the dimensionless form – dimensionless free hydrogen consumption, %; T_0 – is the "time constant" of the process, $T_0 = C_H R_D$, where C_H – is the ultimate hydrogen intensity of the sample; R_D – is the diffusion resistance of the hydrogen absorption process, which is equal to: $R_D = L/(F \cdot D)$, i.e. it combines all physical quantities that are conditionally defined in this consideration.

For the entire chain of successive diffusion resistances on the path of hydrogen from the surface to the crystal lattice, we can write:

$$R_D = \sum (R_{D_i}) = \sum [L / (F \cdot D)]_i.$$

Another dependence follows from formula (3): the expression for the current hydrogen intensity of the sample:

$$H(t) = H_{\max} [1 - \exp(-t/T_0)] \quad (4)$$

B. Joint determination of kinetics parameters (H_{\max} , R_D).

Usually, in the processes of hydrogen absorption by metal powders, the parameter $B = t_A/T_0 = 0$, where t_A is the surface activation time. In this case, formula (2) is simplified:

$$H(t) = A(1 - e^{-t/T_0}), \quad (5)$$

where A – is the maximum hydrogen intensity of the sample; T_0 – is a value equal to the product of the

reduced diffusion resistance R_D and the calculated hydrogen intensity of the C_H sample.

Curve (3) can be arbitrarily called the "exponential kinetic curve", which is written in the following form:

$$H(t) = A[1 - \exp(-t/T_0)].$$

To determine the values of the unknown parameters of the curve A and T_0 from the experimental points, it is necessary to carry out at least two measurements and solve the system of two equations with two unknowns:

$$\begin{cases} H_1 = A[1 - \exp(-t_1/T_0)] \\ H_2 = A[1 - \exp(-t_2/T_0)]. \end{cases}$$

Since the exponent is not an algebraic function, we obtain a system of two transcendental equations with two unknowns, which in the general case has no solution and can only be exactly solved in some special cases, for example, for $t_2 = 2t_1$. If we substitute $t_2 = 2t_1$ in second equation of the system, then we get:

$$\exp(-t_2/T_0) = \exp(-2t_1)/T_0 = [\exp(-t_1/T_0)]^2$$

Introducing a new notation: $\exp(-t_1/T_0) = E$, we obtain an equivalent system of two equations:

$$\begin{cases} H_1 = A(1 - E) \\ H_2 = A(1 - E^2). \end{cases}$$

Her analysis shows that this is a system of two algebraic equations with two unknowns (A and E), which has a solution. It can be obtained, for example, by termwise division of the right and left parts of both equalities. As a result, we get:

$$\frac{H_2}{H_1} = \frac{1 - E^2}{1 - E} = 1 + E,$$

where do we get:

$$E = \frac{H_2}{H_1} - 1 = \exp(-t_1/T_0).$$

From this equality, logarithmizing the right and left sides, we can find the absorption rate M or its inverse value – the "time constant" of the process T_0 :

$$M = (T_0)^{-1} = \frac{1}{t_1} \ln \left[\frac{H_2 - H_1}{H_1} \right]^{-1}.$$

Transforming this expression, we finally get:

$$T_0 = t_1 / \ln \frac{H_1}{H_2 - H_1}.$$

Having obtained from the formula T_0 one can also determine the diffusion resistance: $R_D = T_0/C_H$,

where C_H – is the calculated hydrogen intensity of the experimental sample of mass m .

And now it's enough to simply get the expression for parameter A , since $A = H_{max}$. Substituting the value of E in the system of equations, we obtain:

$$H_{max} = A = \frac{(H_1)^2}{2H_1 - H_2}. \tag{7}$$

EXAMPLE 1

a) On a steep section of the kinetic curve of the process of hydrogen absorption by the TiFe powder intermetallic compound [5] at 303 K, two experimental points on curve 1 (Fig. 3) for which the equality holds: $t_2 = 2t_1$ ($t_1 = 30$ s, $t_2 = 60$ s). We substitute their abscissas t_1 and ordinates ($m \cdot H_1/C_H = 81.1\%$ and $m \cdot H_2/C_H = 87.7\%$) in the formulas obtained for T_0 and H_{max} . Then we get their exact values by the formulas:

$$m \cdot H_{max}/C_H = 88.3\%; T_0 = 12.0$$
 s

b) On a steep section of the kinetic curve of the hydrogen absorption process [5] at 343 K, we select two experimental points on curve 2 (Fig. 3) for which the equality holds: $t_2 = 2t_1$ ($t_1 = 30$ s, $t_2 = 60$ s). We substitute the value of their abscissas t_1 and ordinates ($m \cdot H_1/C_H = 69\%$ and $m \cdot H_2/C_H = 78.9\%$) in the formulas obtained for R_D and H_{max} . And then from the obtained formulas we get their exact values:

$$m \cdot H_{max}/C_H = 80.6\%; T_0 = 16.6$$
 s.

Conclusion: with an increase in the sample temperature by 40 ° C (from 303 K to 343 K), the rate of hydrogen absorption by the TiFe powder intermetallic compound decreases due to an increase in the diffusion resistance R_D by 38%, and the maximum hydrogen capacity of the sample decreases by 9%.

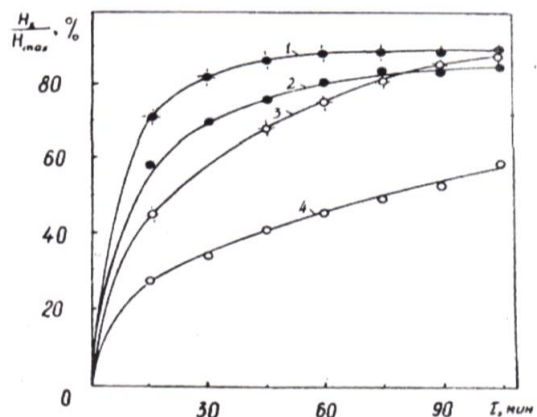


Fig. 3: The dependence of the relative amount of absorbed hydrogen ($H/H_{max}, \%$) on time (t , sec) at 303 (2, 4) and 343 K (1, 3): 1.2 powder TiFe intermetallic compound; 3,4 - 50TiFe – 50Ni composite.

EXAMPLE 2

a) On a steep section of the kinetic curve of the process of hydrogen absorption into the sample (pressed powder) Ti₂Ni [6] upon its destructive hydrogenation at 773 K, two experimental points on curve 1 (Fig. 2) for which the equality holds: $t_2 = 2t_1$ ($t_1 = 25$ min, $t_2 = 50$ min). We substitute their abscissa t_1 and ordinates ($H_1 = 305$ ml/g and $H_2 = 351.5$ ml/g) in the formulas obtained for T_0 and H_{max} . Then we get their exact values by the formulas:

$$H_{max} = 360 \text{ ml/g}; T_0 = 13.1 \text{ min.}$$

b) On a steep section of the kinetic curve of the process of hydrogen absorption into the sample (pressed casting) Ti₂Ni [6] during its destructive hydrogenation at 773 K, two experimental points on curve 2 (Fig. 2) for which the equality holds: $t_2 = 2t_1$ ($t_1 = 50$ min, $t_2 = 100$ min). We substitute their abscissa t_1 and ordinates ($H_1 = 273.7$ ml/g and $H_2 = 347.4$ ml/g) in the formulas obtained for T_0 and H_{max} . Then we get their exact values by the formulas:

$$H_{max} = 356.7 \text{ ml/g}; T_0 = 38.1 \text{ min.}$$

Conclusion: the analysis of the difference in the values of the maximum specific hydrogen consumption of the pressed powder sample and the pressed ingot sample is less than 1% (0.9%), which speaks in favor of the high accuracy of the adopted theoretical model. The diffusion resistance to the flow of hydrogen in the pressed ingot is almost three times higher than in the sample from the pressed powder, this estimate can be obtained from the ratio:

$$R_{D1}/R_{D2} = T_{01}/T_{02} = (38.1 \text{ min})/(13.1 \text{ min}) = 2.9.$$

C. Joint determination of two kinetics parameters (R_D, t_A).

Suppose that R_D, t_A are among the unknowns, and the maximum specific hydrogen intensity of the sample H_{max} is a known quantity. In this case, if the process of hydrogen absorption in metals does not begin immediately after contact with hydrogen due to the very long “activation time” t_A , it is obvious that it is necessary to establish the value of t_A , by which, by the way, one can judge the mechanism of the surface activation process.

To determine the unknowns, it is necessary to choose three points on a steep section of the kinetic curve (moreover, on its convex part): t_1, t_2, t_3 , for which $t_2 - t_1 = \delta = t_3 - t_2$. Thus, we obtain three equations:

$$\begin{aligned} H_1 &= H_{max} - \Delta_1, \\ H_2 &= H_{max} - \Delta_2, \\ H_3 &= H_{max} - \Delta_3. \end{aligned}$$

Using the coordinates of the midpoint on a steep section of the exponent, you can write:

$$\Delta_i = H_{max} \exp\left[B - (t_2 \pm \delta) / T_0\right].$$

Hence, based on the analysis of this ratio, we can compose a system of equations:

$$\begin{cases} \Delta_1 = H_{max} \exp\left[B - (t_2 - \delta) / T_0\right] \\ \Delta_3 = H_{max} \exp\left[B - (t_2 + \delta) / T_0\right]. \end{cases}$$

Substituting the expressions Δ_i into this system of equations and logarithmizing both sides of the equalities, we obtain:

$$\begin{cases} B - (t_2 - \delta) = T_0 \ln(\Delta_1 / H_{max}) \\ B - (t_2 + \delta) = T_0 \ln(\Delta_3 / H_{max}). \end{cases}$$

Solving this system of equations with respect to T_0 , we obtain:

$$T_0 = 2\delta / \ln(\Delta_1 / \Delta_3) = 2\delta / \ln \frac{H_{max} - H_1}{H_{max} - H_3},$$

(8)

From here we can determine: $R_D = T_0 / C_H$, knowing a priori the value of C_H .

The second unknown is determined from the expression for $B = t_A / T_0$:

$$t_A = t_2 - T_0 \cdot \ln \frac{H_{max}}{\sqrt{(H_{max} - H_1) \cdot (H_{max} - H_3)}}. \quad (9)$$

EXAMPLE 3

On the steep section of the kinetic curve (3) of the hydrogen absorption process (Fig. 2), during the destructive hydrogenation of the Ti₂Ni intermetallic compound, there are three experimental points for which the equality holds: $t_2 - t_1 = \delta = t_3 - t_2$ ($t_1 = 112$ min, $t_2 = 132$ min, $t_3 = 152$ min and $\delta = 20$ min). We assume that the value of H_{max} in this case is also equal to 360 ml/g. Substituting in the formula (8) H_{max} and the ordinates H_1 and H_3 of two experimental points, we obtain that the “time constant” $T_0 = 15.0$ min. Then, substituting the values of t_2 and T_0 , as well as the ordinates H_1 and H_3 , we obtain from the formula (9) the value of the “activation time” $t_A = t_2 - 25,0 = 107$ min.

D. Determination of the activation energy of the process of absorption of H₂ by metal.

Since the diffusion resistance R_D in the process of hydrogen absorption by the metal includes the diffusion coefficient D , the values of R_D can be used to determine the activation energy Q_A , which determines the dependence of the diffusion coefficient on absolute temperature. This formula was obtained by the Swedish scientist Svante Arrhenius in 1889 to estimate the speed of chemical processes in the form:

$$D \sim \exp\left(-\frac{Q_A}{RT}\right),$$

where $-$ is the activation energy of the chemical process, J/mol; R is the universal gas constant ($R = 8.31$ J/mol·K); T – is the absolute temperature, K.

Theoretically calculated values of the activation energy Q_A for hydrogen diffusion in metals are: Al (0.47 eV), Cu (0.4 eV), Ag (0.326 eV), Au (0.245 eV). But these values were obtained [4] for a “perfect” crystal lattice without the presence of grain boundaries and without the presence of dislocations in the grain lattice itself. In real cases, the “diffusion” values of Q_A can differ greatly depending on the size of the grains, their relative orientation, and the concentration of dislocations in the crystal lattice of grains.

To determine the value of the activation energy Q_A , it is necessary to have at least two experimentally found values of the diffusion resistance R_D at two different temperatures of the process of hydrogen absorption by a specific sample (powder, compact or plate).

So, for diffusion resistance, we can write:

$$R_D \sim \exp\left(\frac{Q_A}{RT}\right),$$

and for the ratio $R_D(T_1)/R_D(T_2)$ at $T_2 > T_1$ we get:

$$R_D(T_1)/R_D(T_2) = \exp\left[\frac{Q_A}{R}\left(\frac{1}{T_1} - \frac{1}{T_2}\right)\right].$$

Where can we express the activation energies of Q_A :

$$Q_A = R \frac{T_1 \cdot T_2}{T_2 - T_1} \cdot \ln \frac{R_D(T_2)}{R_D(T_1)}.$$

EXAMPLE 4

If, as a result of studying the kinetics of the process of hydrogen absorption by a metal sample at two different temperatures, two diffusion resistance values $R_D(T_1)$ and $R_D(T_2)$ were obtained for it, then using the formula (10), we can estimate the activation energy Q_A of the process.

Example 1 establishes the values of the “time constants” of the kinetic curve $T_0 = C_H R_D$ for two experiments (processes of hydrogen absorption by the 50TiFe – 50Ni powder intermetallic compound) at different temperatures ($T_1 = 303$ K, $T_2 = 343$ K). Since the formula for determining the activation energy Q_A does not use the absolute values of $R_D(T)$, but their ratio, in this case we can use the equality:

$$R_D(T_1)/R_D(T_2) = T_0(T_1)/T_0(T_2),$$

since the value of C_H is the same in both cases. Thus, we have:

$$Q_A = R \cdot [(303 \cdot 343)/(343 - 303)] \cdot \ln(16.6/12.0) = 7.0 \text{ kJ/mol.}$$

Conclusion: analysis of the obtained result gives every reason to believe that hydrogen enters the TiFe powder intermetallic sample precisely by diffusion, since it is known [4] that the activation energy Q_A for the process of hydrogen diffusion in metals is of the order of ~10 kJ/mol.

IV. CONCLUSIONS

The article developed analytical methods for calculating the parameters of the kinetics of hydrogen absorption in metals from a very limited sample of experimental process data based on an exponential mathematical model of kinetics and then characteristic physical complexes (parameters of the kinetic model).

Based on the original solutions of the systems of two transcendental equations, express methods have been developed for determining the parameters of the kinetic model: the maximum specific hydrogen consumption of the metal H_{\max} , diffusion resistance to the hydrogen flow R_D and the activation time of its surface t_A based on a limited selection of experimental data (2-3).

It has been established that it is possible to determine the maximum specific hydrogen intensity H_{\max} of a metal if it forms a solid solution with hydrogen, which allows one to calculate the coefficient in the Siverts formula.

The possibility of determining the maximum hydrogen intensity H_{\max} in the case where hydrogen hydrates the metal is found, which also makes it possible to establish the mass of the metal, which at the same time reacted with hydrogen.

In this work, a formula is obtained for determining the activation energy Q_A of the process of hydrogen absorption by a metal if the diffusion resistance R_D of the sample was obtained in experiments at two different temperatures.

The formulas obtained in this paper can also be used to estimate parameters of other chemical and physical processes, the rate of which decreases exponentially with time.

REFERENCES

- [1] Bratanich T.I., Ludanov K.I. et al. New Method and Autonomous Installation for Solar Energy Chemical Accumulation by Hydrogen // World Hydrogen Technologies Convention (BOOK OF ABSTRACTS WHTC-2007, Editors T.N. Veziroglu – Spazzafumo G.). – Montecatini Terme, Italy. – 2007, p. 101–102.
- [2] Ab E.A., Plotnikov R.I., Khutsishvili L.A. Hydrogen sorption by titanium and zirconium at low pressure // Zh.T.Ph. – 1959. – T. 29 – No. 8 – S. 1146–1151.
- [3] Kogan Y.D., Kolachev B.A. et al. Constants of the interaction of metals with gases. Directory. – M.: Metallurgy, 1987. – 368 p.
- [4] Nikulin V.K., Potekhina N.D. Theory of dissolution and diffusion of hydrogen in metals // Zh.Ph.Ch. – 1980. – T. 14. – No. 11. – S. 2751–2756.
- [5] Bratanich T.I., Solonin S.M. Study of the rate of interaction with hydrogen of TiFe–Ni powder compositions // Modern problems of physical materials science. Proceedings of the IPMS NASU. Vol. 17. Kiev-2008. – S. 169–174.
- [6] Skorohod V.V., Bratanich T.I. Thermodynamics, structural mechanics, and the kinetics of destructive hydrodynamic technology intermetallic // Physicotechnical problems of modern materials science. In 2 vols., T.2. NAS of Ukraine. – K.: Akadempriodika, 2013. – S. 7–32.