Devices and Methods of Measurements
2023, vol. 14, no. 2, pp. 145–151
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DOI: 10.21122/2220-9506-2023-14-2-145-151

Methodology for Determining the Effective Thickness of the Cemented Layer of Steel

Sergei G. Sandomirski, Aleksandr L. Val'ko, Sergej P. Rudenko

*Joint Institute of Mechanical Engineering of the National Academy of Sciences of Belarus,
Akademicheskaya str., 12, Minsk 220012, Belarus*

Received 04.04.2023
Accepted for publication 24.05.2023

Abstract

Highly loaded transmission gears are cemented and hardened. An important parameter of the hardened cemented layer is its effective thickness h_{ef}. Metal banding and the unavoidable instrumental error in hardness measuring have a great influence on the reliability of h_{ef} determination. The purpose of this article was to develop a methodology to improve the reliability of determining of the effective thickness h_{ef} of the hardened layer in steel after carburizing and quenching.

The value of h_{ef} is the distance h from the surface of the product to the hardness zone of 50 HRC. The article substantiates that approximation of hardness change from the distance h to the product surface will allow to obtain a more reliable dependence of hardness change in the investigated area when making hardness measurements in a wider range of distance h. Therefore, to increase the reliability of h_{ef} determination, results of the HV0.5 hardness measurement in an extended range of changes in h in the vicinity of the analyzed zone were used. The HV0.5 measurement results are converted to HRC hardness values using the formula recommended by the international standard. The HRC(h) distribution of HRC hardness values in the measurement area is interpolated by a second-degree polynomial which physically correctly reflects the change in metal hardness in the analyzed area. The resulting polynomial is used to determine of the distance hef at which the hardness takes on a value of 50 HRC. The methodology was used to determine the h_{ef} of an 18KhGT steel gear wheel after carburizing and quenching. It is shown that results of two independent measurements of the h_{ef} sample differ from each other by 0.003 mm. This is significantly less than the permissible error of 0.02 mm of the h_{ef} determination according to the standard technique. The error of h_{ef} determination is reduced by extending the range of variation of h and statistically valid interpolation of the monotonic change in hardness with the distance from the surface of the item in the measurement area.

The developed method of determining the effective thickness h_{ef} of the hardened steel layer consists in determining the distribution of its hardness in the expanded vicinity of the h_{ef} area, approximating the obtained dependence by a polynomial of the second degree and solving the square equation obtained with its use. The technique provides a significant reduction in the influence of the structural banding of the metal and the inevitable error in measuring hardness on the result of determining the h_{ef}. Its application will allow to optimize the cementation regimes of gear wheels to increase their service life.

Keywords: surface hardening, cementing, hardness, interpolation of hardness distribution, effective thickness of the hardened layer

Адрес для переписки:
Сандомирский С.Г.
Объединенный институт машиностроения Национальной академии наук Беларуси,
ул. Академическая, 12, г. Минск 220012, Беларусь
e-mail: sand_work@mail.ru

Address for correspondence:
Sandomirski S.G.
Joint Institute of Mechanical Engineering of the National Academy of Sciences of Belarus,
Akademicheskaya str., 12, Minsk 220012, Belarus
e-mail: sand_work@mail.ru

Для цитирования:
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Методика определения эффективной толщины цементированного слоя стали

С.Г. Сандомирский, А.Л. Валько, С.П. Руденко

*Объединенный институт машиностроения Национальной академии наук Беларуси,
ул. Академическая, 12, г. Минск 220012, Беларусь*

Поступила 04.04.2023
Принята к печати 24.05.2023

Высоконагруженные зубчатые колёса трансмиссий подвергают цементации и закалке. Важным параметром упрочнённого цементированного слоя является его эффективная толщина h_{ef}. Большое влияние на достоверность определения h_{ef} оказывают полосчатость металла и неизбежная инструментальная погрешность измерения твёрдости. Цель работы – разработка методики повышения достоверности определения эффективной толщины h_{ef} упрочнённого слоя в стали после цементации и закалки.

За величину h_{ef} принимают расстояние h от поверхности изделия до зоны с твёрдостью 50 HRC. В работе обосновано, что аппроксимация изменения твёрдости от расстояния h до поверхности изделия позволит получить более достоверную зависимость изменения твёрдости в исследуемой зоне при проведении измерений твёрдости в более широком диапазоне расстояний h. Поэтому для повышения достоверности определения h_{ef} использованы результаты измерения твёрдости HV0,5 в расширенном диапазоне изменений h в окрестности анализируемой зоны. Результаты измерения HV0,5 пересчитаны в значения твёрдости HRC по формуле, рекомендованной международным стандартом. Распределение HRC(h) значений твёрдости HRC в области измерения интерполировано полиномом второй степени, физически верно отражающим изменение твёрдости металла в анализируемой зоне. Полученный полином использован для определения расстояния h_{ef}, при котором твёрдость принимает значение 50 HRC. Методика использована для определения h_{ef} зубчатого колеса из стали 18ХГТ после цементации и закалки. Показано, что результаты двух независимых измерений h_{ef} образца отличаются друг от друга на 0,003 мм. Это существенно меньше допустимой погрешности 0,02 мм определения h_{ef} по стандартной методике. Погрешность определения h_{ef} снижена за счёт расширения диапазона изменения h и статистически обоснованной интерполяции монотонного изменения твёрдости с расстоянием от поверхности изделия в области измерения.

Разработанная методика определения эффективной толщины h_{ef} упрочнённого слоя стали заключается в определении распределения её твёрдости в расширенной окрестности области h_{ef}, аппроксимации полученной зависимости полиномом второй степени и решении полученного с его использованием квадратного уравнения. Методика обеспечивает существенное снижение влияния структурной полосчатости металла и неизбежной погрешности измерения твёрдости на результат определения h_{ef}. Её применение позволит оптимизировать режимы цементации зубчатых колёс для повышения ресурса их эксплуатации.

Ключевые слова: поверхностное упрочнение, цементация, твёрдость, интерполяция распределения твёрдости, эффективная толщина упрочнённого слоя

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Introduction

For long and reliable operation of mobile machinery transmissions, the hardness in the area of maximum deep contact stresses occurring at some distance from the gearing surface is important [1, 2]. Cementation (saturation of the surface layer of low-carbon steel with carbon) followed by hardening is the main method of surface hardening steel to the required depth [3–7]. This chemical heat treatment (CHT) forms a surface layer in low-carbon steel with a decreasing concentration of carbon from the surface to the core of the part. Cemented quenching produces high-carbon martensite in the surface layer with high hardness and wear resistance, while the core retains low hardness and high toughness (Figure 1).

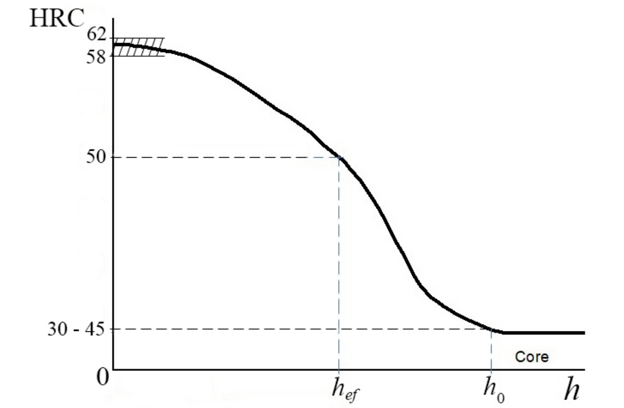

Figure 1 – Diagram of changes hardness HRC in cemented steel from the distance h to the carbon saturation surface. h_{ef} and h_0 – effective and total thickness of the cemented layer

Surface hardness and effective h_{ef} thickness of the cemented layer are regulated to ensure the required service life of the gears [8, 9]. These values determine the technology of hardening of gears and their strength. The distance from the surface to the zone of the layer with hardness 50 HRC is taken as h_{ef} after hardening [8, 10]. To determine hef, the results of measurements of hardness distribution HV0.5 on thin sections along the depth h of cemented layer of samples are used (Figure 2).

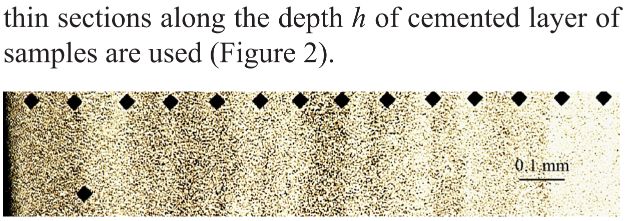

Figure 2 – Indentor impressions during Vickers hardness measurement on thin sections of a sample of rolled steel 20XH3MA after carburizing, high tempering, hardening from 820 °C and low tempering. Carbon saturated surface of the sample is located on the left side of the figure

Measurements of the hardness distribution of steels and alloys in the area of maximum stresses or in the area of metal failures caused by them are widely used in metal science and mechanical engineering [8–14]. But methods for determining the nature of the change in the properties of the metal with distance to its surface are not productive and not accurate enough. Studies have shown that the presence of a banded structure in the measurement area (Figure 2), as well as due to the inevitable measurement error of HV0.5, the validity of such a determination of h_{ef} is insufficient. The purpose of this article was to develop a methodology to improve the reliability of determining the effective thickness of the h_{ef} hardened layer in steel after carburizing and quenching.

Analysis of the standard method for determining the h_{ef} of a cemented layer

To determine h_{ef}, multiple measurements of hardness HV0.5 are used on a specially prepared slab of the product, perpendicular to its surface, in the immediate vicinity of the area where the hardness of the metal is close to the value of 50 HRC [10]. The results of HV0.5 measurements are recalculated into HRC hardness values. According to the results of these measurements and recalculation, construct a relationship HRC(h). The value of h, at which the hardness equals 50 HRC, is considered equal to the value of h_{ef}. Studies have shown that the presence of a banded structure in the measurement area (Figure 2), as well as due to the inevitable measurement error of HV0.5, the accuracy of such a determination of h_{ef} is insufficient.

This is illustrated by the results of determining the HRC hardness distribution over the thickness h of the cemented layer of an experimental sample of 18KhGT steel near the h_{ef} area (Figure 3).

The equation of the linear trend line of the correlation field of hardness change HRC with distance h from the cemented surface of the witness sample according to Figure 3 has the following form:

$$\text{HRC} = 56.76–3.5h(\text{mm}). \qquad (1)$$

From (1) the effective thickness h_{ef} of the cemented layer of the witness sample (for a hardness value of 50 HRC) is 1.931 mm.

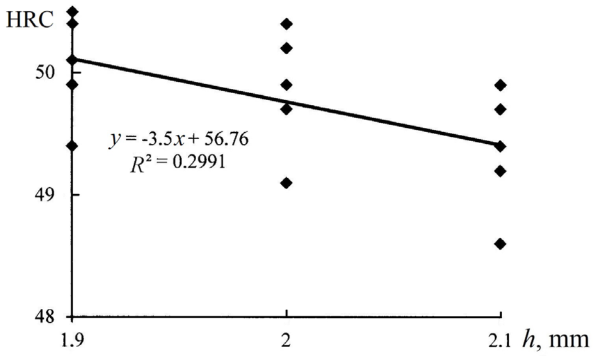

Figure 3 – The results of determining the HRC hardness distribution over the thickness h of the cemented layer of the experimental sample near the area of h_{ef}

But the reliability of R^2 approximation (square of the R correlation coefficient between HRC and h) of the experimental dependence HRC(h) by the trend line (1) was only 0.2991. This indicates that the reliability of the determination of the value of h_{ef} using equation (1) is not high. The results presented in Figure 3 show that increasing the number of hardness measurements in the specified zone, as recommended by the standard method [10], did not lead to an increase in the reliability of determining the h_{ef}.

Prerequisite for developing a method to improve the reliability of determining the effective thickness of the cemented layer of steel

In [15] it is shown that the limits of achievable value R_{max} of correlation coefficient between measurement results and true values of physical quantity are determined not only by the relative error δ of its measurement, but also by the relative range d of its change. Increasing the number of measurements (in the presence of an error of each measurement) in a narrow range d of variation of the varied parameter practically does not lead to a decrease in the error of determining the correlation between the true values of the physical quantity and the indirect results of its measurement.

To solve this problem, let us take advantage of the fact that an increase in d with constant δ leads to an increase in the achievable R_{max} correlation coefficient between the measurement results and the true values of the physical quantity [15]. Therefore, approximation of change of the measured physical quantity (in this case – HRC hardness) from the changing parameter (distance h from the surface) will allow to obtain more reliable HRC(h) dependence when measuring in a wider range of h parameter change. On the basis of the obtained approximation (with physically correct reflection of the nature of change of the studied dependence), a more accurate value of the parameter h will be obtained, at which the measured value is equal to the given value of HRC.

To justify this, let us use the obtained in [15] dependence of the achievable coefficient R_{max} of correlation between the measurement results and the true values x of the physical quantity on the relative error δ of its measurement and the relative range d of change ($d = (x_{max} - x_{min})/x_{max}$). For the dependence $R_{max} = R_{max}(\delta, d)$ in the range of $R_{max} \geq 0.8$ in [15] a formula was developed that approximates this dependence with sufficient accuracy:

$$R_{max} \approx 1 - 0.866\delta^{1.82} d^{-2.25}. \quad (2)$$

In Figure 4 the dependence $R_{max} = R_{max}(\delta, d)$ is plotted for the value δ = 4 %, which is typical for the relative error of HV hardness measurement by Vickers.

The analysis of the dependence $R_{max} = R_{max}(d)$ presented in Figure 4 showed, for example, that an increase in the parameter d by 3 times (from 0.2 to 0.6) reduces the difference $(1 - R_{max})$ by an order of magnitude: from 0.092 to 0.0078. That is, it radically increases the reliability of approximation of the required dependence (coefficient R^2 of "reliability of approximation" increased from 0.824 to 0.984).

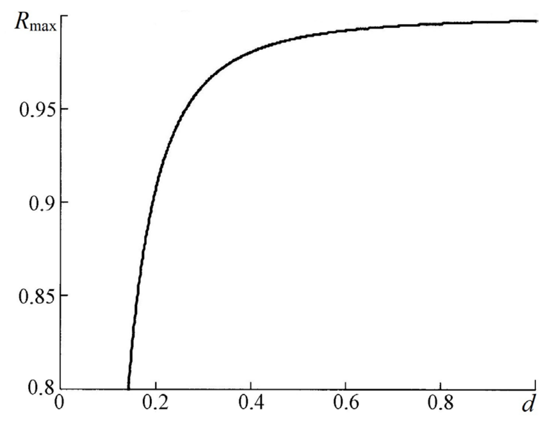

Figure 4 – Dependence of the maximum achievable correlation coefficient R_{max} between the measurement results and the true values of the physical quantity on the relative range d of its variation at the relative error of measurement δ = 0.04. Calculating by the formula (2)

The increase in the reliability of determining the effective thickness of the cemented layer when using this approach to its determination will be illustrated by the following example.

Model sample of 18KhGT steel and the method of measuring its parameters

One of the steels used for the production of medium modulus gears is 18KhGT steel. The sample (30 mm in diameter and 10 mm in thickness) used for research (the results of which are presented in Figure 3 and 5) was subjected to carburizing and hardening according to the regimes regulated by the production of power transmission gears [8]. The distribution of microhardness HV0.5 over the depth of the cemented layer of the sample after chemical treatment was measured on a microhardness sensor PMT-3M at a load of 4.9N[1]. To determine the effective thickness h_{ef} of the cemented layer of the sample, the measured values of microhardness HV0.5 were recalculated into HV hardness units (at a load of 30 Kg) with a conversion factor of 0.97 [16] and into HRC hardness values according to the formula recommended by the standard[2]:

$$\mathrm{HRC} = 31.49 + 0.0796683 \cdot \mathrm{HV} - \\ -0.0000355432 \cdot \mathrm{HV}^2 - \frac{6728.16}{\mathrm{HV}}. \tag{3}$$

The results of recalculation of the measured values of microhardness HV0.5 into HRC hardness values in the range of HRC hardness values of the model sample, which is practically important for determination of the effective h_{ef} thickness of the cemented layer, are shown in Figure 5. Note that the results of determining the HRC values of the sample at a given value of *h* differ significantly for two independent measurements (Figure 5*a*, *b*).

The dependences of HRC(*h*) obtained in Figure 5 dependences were approximated (Figure 5) by second-degree polynomials, respectively:

$$\mathrm{HRC} = 12.662h^2–59.55h+117.46; \tag{4}$$

$$\mathrm{HRC} = 13.052h^2–60.597h+118.01. \tag{5}$$

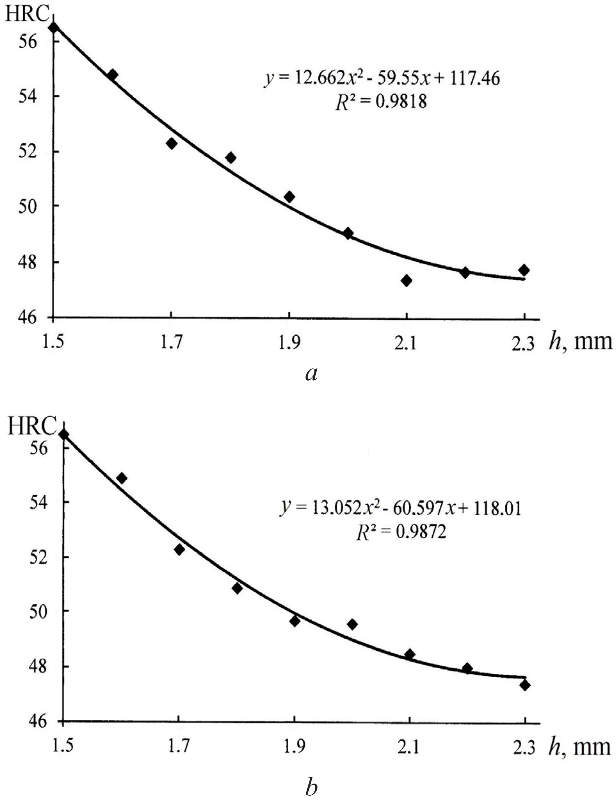

Figure 5 – HRC hardness distributions (recalculated by formula (3) according to the results of HV0.5 hardness measurements) by thickness *h* of the cemented layer of the experimental sample (in the nearest and farthest vicinity of the area h_{ef}) after hardening. Interpolating their analytical dependences with power regression equations and R^2 coefficients of approximation reliability. *a*, *b* – results of two independent measurements

According to [10] (Figure 1), the value of the effective thickness h_{ef} of the cemented steel layer after hardening corresponds to the value of 50 HRC. In accordance with this, on the basis of dependences (4) and (5), the following quadratic equations were obtained to determine the h_{ef} of the sample:

$$h_{ef}^2 - 4.703 \cdot h_{ef} + 5.3278 = 0; \tag{6}$$

$$h_{ef}^2 - 4.6427 \cdot h_{ef} + 5.2107 = 0. \tag{7}$$

The results of solving equations (6) and (7) were, respectively: h_{ef} = 1.902 mm and h_{ef} = 1.899 mm. They differ from each other by 0.003 mm, which is significantly less than the allowable error of 0.02 mm of determination of h_{ef} in accordance with [10].

The inevitable banding (Figure 2) of the sample and the error in each hardness measurement did not go anywhere. The induced error of the hardness

[1] ISO 6507-1:2005. Metallic materials – Vickers hardness test – Part 1: Test method (IDT)

[2] Standard Hardness Conversion Tables for Metals Relationship Among Brinell Hardness, Vickers Hardness, Rockwell Hardness, Superficial Hardness, Knoop Hardness, and Scleroscope Hardness / Designation: E140 – 07)

measurement takes place in every measurement (Figure 5). But, thanks to the methodology used to determine h_{ef}, these errors have almost no effect on the result of determining h_{ef}.

Conclusion

A technique for determining of the effective thickness h_{ef} of the cemented steel layer by determining its hardness HRC in the expanded vicinity of the h_{ef} area, approximating the obtained dependence by a polynomial of the second degree reflecting the character of the HRC hardness of the cemented steel on the distance to its surface in this area, and then solving the square equation obtained with its use, is proposed.

The proposed method provides a significant reduction in the influence of structural striping of the metal and the inevitable error in measuring hardness on the result of h_{ef} determining. This will allow more accurate setting of cementing regimes of gears increasing their service life under increased loads.

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