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Computer-Aided Evaluation of Quenching Intensity and Prediction of Hardness Distribution

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Abstract. A new computer-aided method is described for measuring and recording quenching intensity under workshop conditions using a special cylindrical probe. The method is based on measuring the temperature gradient at the probe surface and representing the quenching intensity as heat flux density. The method is applicable for different quenchants, quenching conditions, and quenching techniques, and enables the comparison of the real quenching intensity among them. The technique is sensitive enough to reflect a change in each quenching parameter.

A test specimen made of the steel grade of interest is hardened under the same quenching conditions as round bars of different diameters made of the same steel grade, in order to predict the hardness distribution across such bars. This computer-aided prediction is based on Jominy hardenability data, quenching intensity characteristics, and hardness distribution data obtained by quenching test specimens—all stored in the computer memory. Using equations from a regression analysis of Crafts-Lamont diagrams, software was developed for precise prediction of the hardness distribution in quenched bars. Predicted values are compared with experimentally obtained results.

INTRODUCTION

A knowledge of quenching intensity is required in order to predict hardness distribution after quenching steel bars of defined diameter and hardenability. The quenching intensity in the physical sense is the abililty of the quenching medium to extract heat from a metal part, and can be described by the heat flux density on its surface (MW/m^2). Quenching a typical workpiece such as a 50 mm diameter cylinder takes some hundreds of seconds, and the quenching intensity changes during this time. To characterize the quenching intensity by a single number such as the Grossman "H" value is not rigorously correct and not always explicit enough. An "H" value of 1.0 may be associated with water without agitation, but it may also be associated with vigorously agitated oil.

The quenching intensity in practice depends on many factors. The main ones are: the physical and chemical properties of the quenchant, the temperature of the quenching bath, and the agitation rate and direction. Since most of these factors can be changed independently, it is more correct to refer to quenching conditions rather than to a specific quenchant. This is especially true when different quenching techniques such as direct quenching, interrupted quenching, and martempering are considered.

When the Technical Committee on Scientific and Technological Aspects of Quenching (IFHT) prepared its five-year working plan in 1980, the Committee was fully aware of differences between laboratory methods for measuring the quenching power of a specific quenchant and practical methods for measuring quenching intensity in a heat treat shop. As a result, we have today the internationally recommended Laboratory Test for Assessing the Cooling Characteristics of Quenching Oils, based on the Wolfson Heat-Treatment Engineering Group method. However, for practical measuring and recording quenching intensity in the shop, there is as yet no widely recognized method. Currently, there are a great number of different quenchants with numerous different quenching conditions. A practical method for evaluating quenching intensity should be applicable for all quenchants, quenching

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conditions, and quenching techniques, and thereby enable comparisons of quenching intensity. Moreover, the method should provide the basis for automatic control of quench intensity during the quenching process, and be sufficiently sensitive to reflect changes in each of the above-mentioned parameters.

A NEW METHOD AND EQUIPMENT FOR MEASURING AND RECORDING OF THE QUENCHING INTENSITY UNDER SHOP CONDITIONS

The new method for measuring and recording quenching intensity is applicable to all quenchants, quenching conditions, and quenching techniques. It is based on the known physical rule expressed by the equation:

$$\phi = \lambda x \frac{\partial T}{\partial n} \tag{1}$$

where

Φ = heat flux, that is, quantity of the heat which passes in a unit of time perpendicular to the surface through a unit surface of the probe, W/m^2

λ = thermal conductivity of the probe material, W/Km

$\frac{\partial T}{\partial n}$ = temperature gradient across the probe surface, perpendicular to the surface, (K/m)

The heat flux at the surface of a body is directly proportional to the temperature gradient at the surface multiplied by the thermal conductivity of the body material [1,2]. The essential feature of the new method lies in measuring and recording the temperature gradient at the surface of a special cylindrical probe during the entire quenching process. Since the conductivity of low alloy steel changes only about 15% in the temperature range of 800°C to 100°C [3], the conductivity is taken as a constant in each of three temperature regions for thermal calculations.

The temperature on the surface itself and the temperature at a point just underneath the surface should be measured, in order to determine the temperature gradient at the surface. Surface temperature measurement during quenching of a specimen has, until now, been considered to be rather inaccurate, and should not be used in calculations if at all possible. However, using a new concept of fast-response thermocouples for transient thermal measurements, measurement of the surface temperature becomes possible and reproducible.

Temperature measurements should be made on the true surface in order to record as accurately as possible all phenomena that are taking place during quenching (e.g., vapor blanket, boiling, and convection phenomena). It is well known that if the point of temperature measurement is shifted even a little from the surface into the interior of the specimen, the effect of the heat transfer phenomena on the temperature curve will be greatly damped. For measurement of the temperature on the true surface of the probe, the thermocouple must fulfill the following requirements:

- it should be two-dimensional instead of three-dimensional
- it should be flat with the surface
- it should, with its own mass, disturb the heat flux as little as possible

Figure 1 shows a 50 mm diam × 200 mm long cylindrical probe developed in cooperation with the NANMAC Corp., Framingham Centre, Massachusetts (USA). The probe is made of AISI 304 stainless steel, having a gland nut with two thermocouples assembled at mid-length. The outer thermocouple measures the temperature on the surface of the probe, and the second one measures the temperature at a point 1.5 mm below the surface. Both thermocouples are located on the same longitudinal plane, but displaced radially. NANMAC thermocouples, details of which are given on the right side of Figure 1 (U.S. Pat. No. 2,829,185) meet all of the above-mentioned requirements.

The sensing tip of the thermocouple consists of two flat rolled chromel/alumel wires, each 0.025 mm thick, and three mica-isolation layers, each 0.005 mm thick. The whole measuring "sandwich" has a thickness of 0.065 mm and is pressed into the gland nut by means of a split conical wedge. The hot junction of the thermocouple is formed on the probe surface itself by polishing the sensing tip region. During the polishing action, microscopic particles of both metals that form the thermocouple bridge the central mica layer and join together. The specific features of the cylindrical probe are:

- The response time of the thermocouple is 10^{-5} sec; the fastest temperature changes can be recorded.
- The internal thermocouple can be positioned with an accuracy of ±0.025 mm.
- The surface condition of the probe can be maintained by polishing the sensing tip before each measurement.
- The body of the probe, made of an austenitic stainless steel, does not change in structure during the heating–quenching process, nor does it evolve or absorb heat because of phase changes.

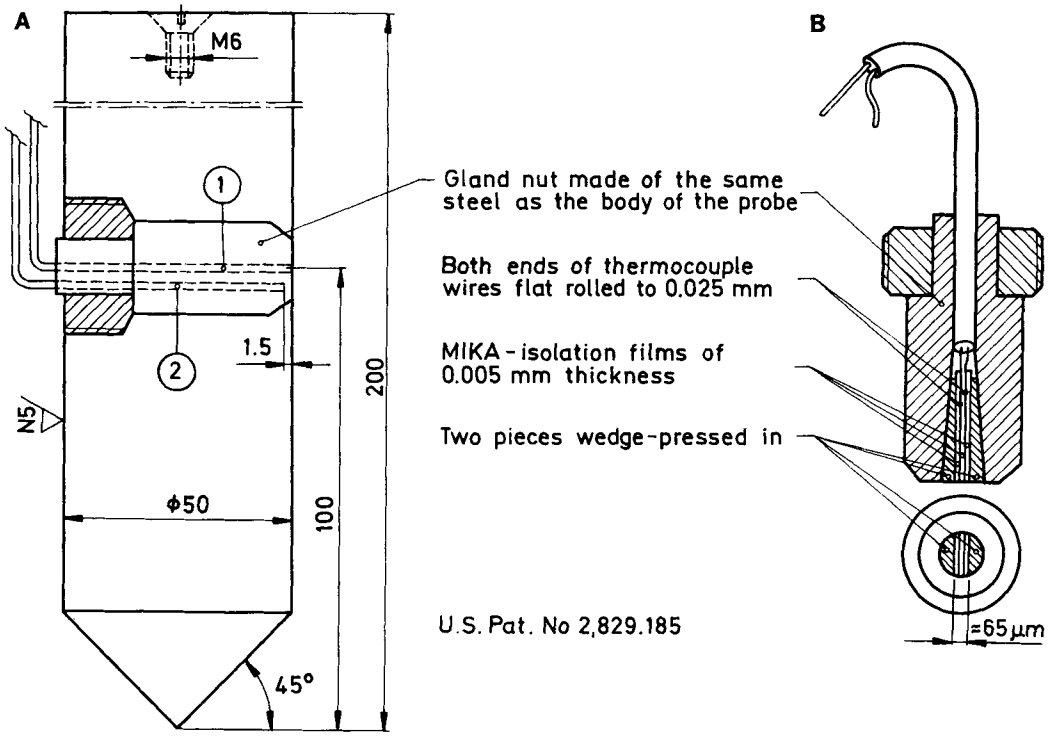

Fig. 1. (A) Liscic–NANMAC probe for measurement of the temperature gradient on the surface. (B) Detail of the NANMAC-thermocouples.

- The size of the probe and its mass ensure a sufficient heat capacity and a symmetrical radial heat flow in the cross-sectional plane where the thermocouples are located.
- The average heat transfer coefficient during the boiling stage generally depends on the specimen diameter, but only for diameters less than 50 mm [4], so in this case the dependence will not develop.

For each practical measurement of the quenching intensity, the probe was first preheated at 400°C for 2.5 hr and subsequently austenitized at 850°C for 1 hr in a protective atmosphere furnace, transferred quickly (in about 3 sec) to the quenching bath, and immersed. The probe was connected to an Apple II microcomputer through an interface having two analog-to-digital converters and two amplifiers. Adequate software was developed to store the temperature versus time data from both thermocouples, and to calculate and graphically display the relevant functions. The temperatures were recorded for 500 sec after immersion in the quenchant using the following sampling frequencies: from 0 to 4 sec each 0.01 sec; from 4 to 20 sec each 0.25 sec, and from 20 to 500 sec each 1 sec. A total of 960 data points were recorded during each quench from each thermocouple.

Figure 2 shows the recorded cooling curves for the surface of the probe and for the point 1.5 mm below the surface (a), as well as relevant heat flux versus time (b), and heat flux versus surface temperature (c) curves obtained by quenching the probe in 20°C mineral oil without agitation. Figure 3 shows the same curves obtained by quenching the probe in water at 20°C without agitation.

On comparison of the diagrams in Figures 2 and 3, it is obvious that the quenching intensity of water is much greater than that of oil. The heat flux versus time curve in Figure 3(B) shows a maximum of 4.3 MW/m^2 compared to 2.3 MW/m^2 in Figure 2(B). High heat flux values during quenching in water are obtained and the maximum value is reached in the third second after immersion of the probe, while for quenching in oil the heat flux maximum is reached in the eighth second after immersion of the probe. During the critical time interval between 1 and 10 sec after immersion, the heat flux values are much higher during quenching in water than during oil quenching, as is seen by comparing Figures 2(B) and 3(B). Comparison between Figures 2(C) and 3(C) (heat flux versus surface temperature of the probe) shows the following important difference between oil and water quenching: that is, while the heat flux maximum during oil quenching occurred in the moment when the surface temperature of the probe reached 420°C, the heat flux maximum for water quenching occurred in the moment when the surface temperature was 170°C.

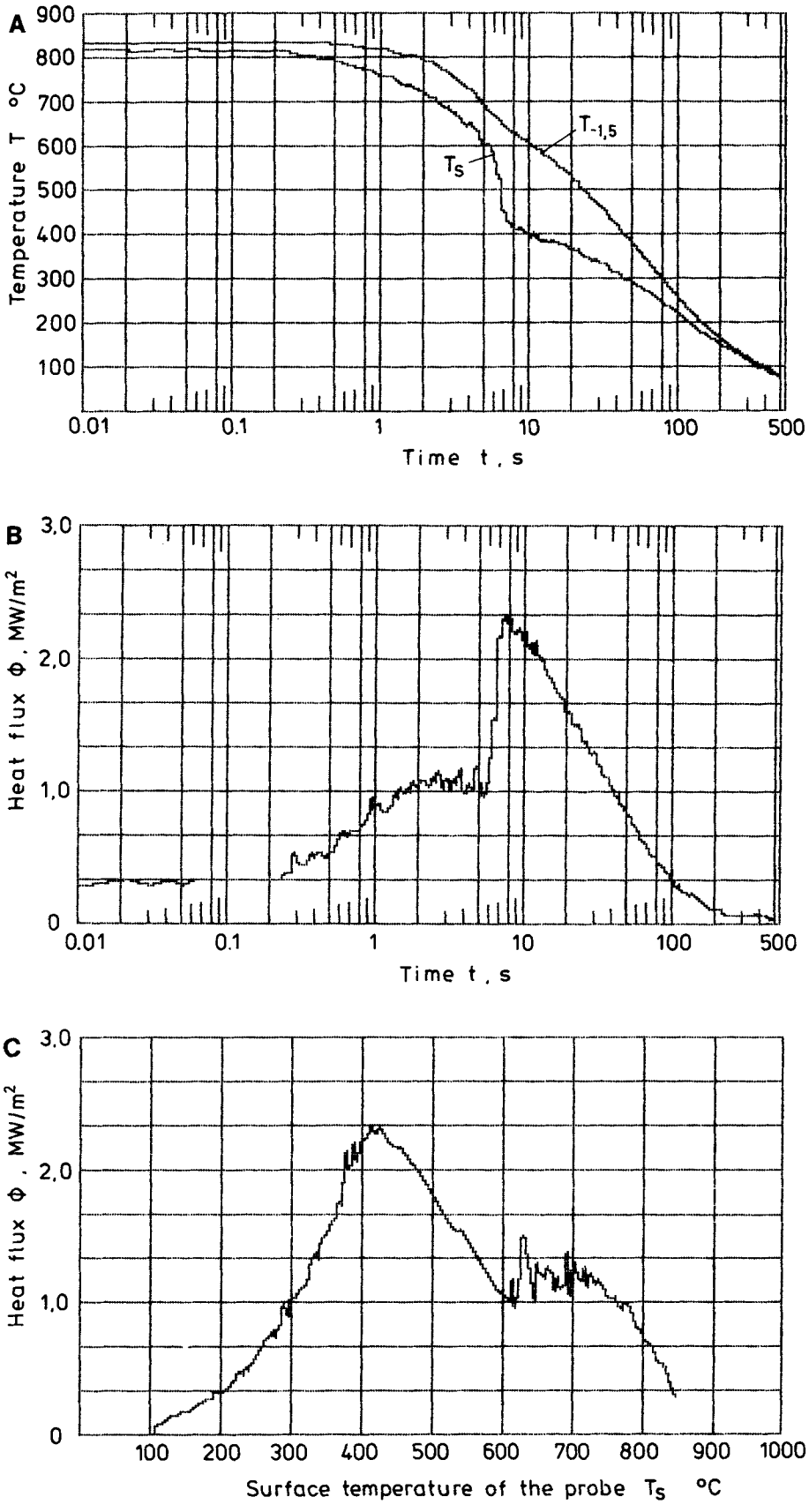

Fig. 2. (A) Recorded cooling curves for the very surface of the probe and for the point 1.5 mm below the surface. (B) Relevant heat flux versus time curve. (C) Heat flux versus surface temperature curve obtained by quenching the probe in a mineral oil at 20° C without agitation.

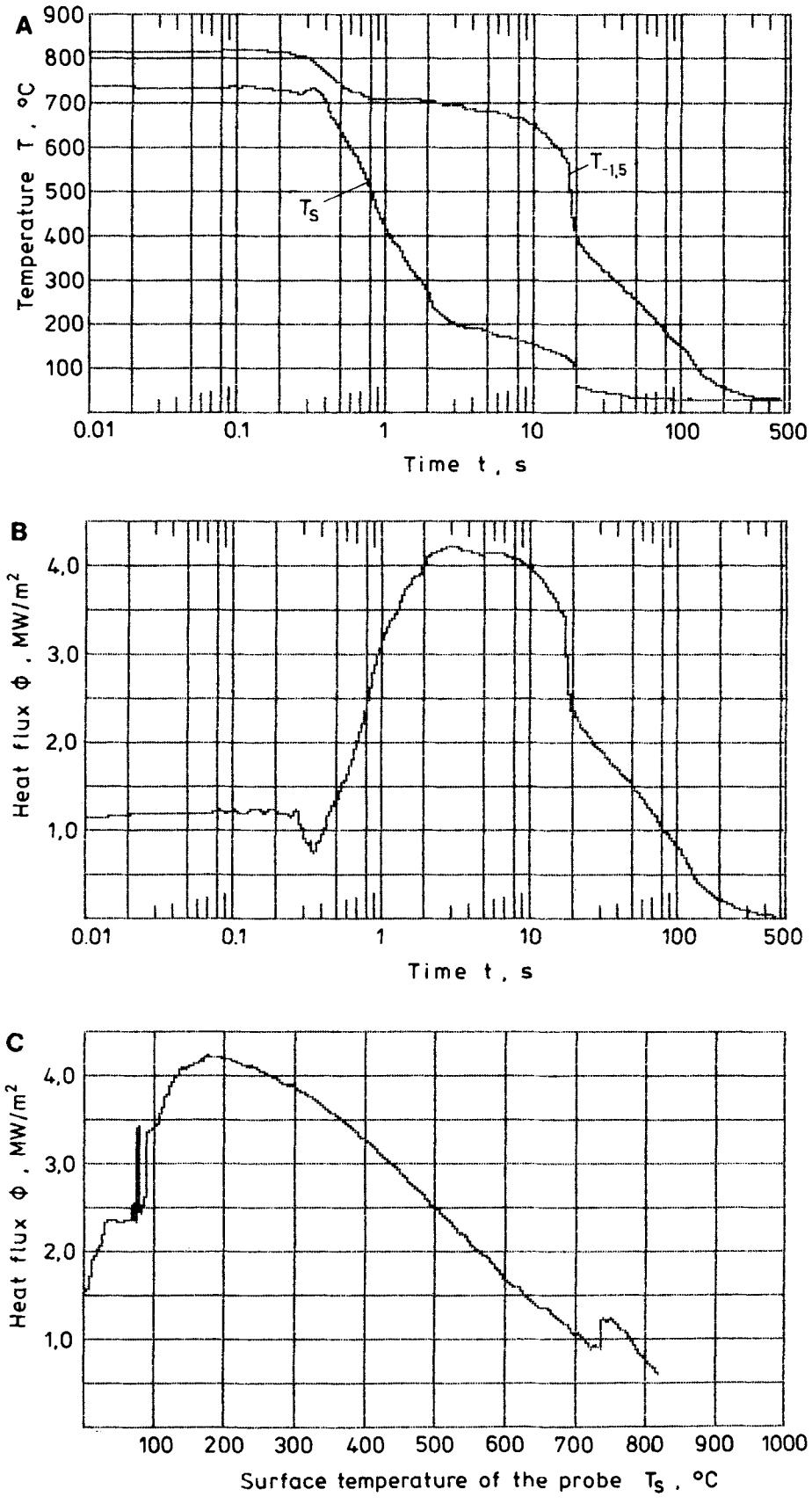

Fig. 3. (A) Recorded cooling curves for the very surface of the probe and for the point 1.5 mm below the surface. (B) Relevant heat flux versus time curves. (C) Heat flux versus surface temperature curve obtained by quenching the probe in plain water at 20°C without agitation.

It is a well-known fact that the cooling rate in the low temperature region is much higher in water quenching than in oil quenching.

The above-described comparison shows how clearly the differences in real quenching intensity can be recorded and explained by the method used.

THE ROLE OF THE TEST SPECIMEN

In order to predict the hardness distribution across round bars of different diameters after quenching under specified conditions, a specimen of the same dimensions as the probe (50 mm dia × 200 mm), and of the same surface conditions, and made of the steel grade in question must be hardened. Jominy hardenability data on the same steel grade and same heat should also be obtained and stored in the computer memory.

In hardening the test specimen, care should be taken to ensure that the austenitizing process and the quenching conditions are equal for the probe and for the test specimen. After quenching, the test specimen should be carefully cut at mid-length, the cross section ground, and the hardness measured along three radii at 120 deg. The average hardness values are then stored in the computer.

Two main uses of the test specimen are:

(a) the hardness distribution is determined across the cross section of the specified steel grade after quenching under specified conditions, and the relevant hardness data at five characteristic points (surface, $^{3}/_{4}$R, $^{1}/_{2}$R, $^{1}/_{4}$R, and center) are stored in the computer memory. This data allows hardness curves obtained under different quenching conditions using the same steel grade to be compared, as well as allowing hardness curves obtained under the same quenching conditions with different steel grades to be compared.
(b) The hardness values measured at five characteristic points and stored in the computer are later transferred to the equivalent Jominy hardenability curve by a method described later in order to obtain the equivalent Jominy distances E_i.

DATA BASE OF JOMINY HARDENABILITY DATA AND QUENCHING INTENSITY CHARACTERISTICS

Several different steel grades are used in every production environment. In order to know their hardenability, representative Jominy hardenability curves for each steel grade should be stored in the computer memory.

In addition, every heat treatment shop deals with a range of quenching facilities and quenching conditions. It should be emphasized that the number of different quenching conditions is much greater than the number of existing quenching facilities, because by changing any one of the operating parameters different quenching intensities are obtained.

Quenching intensity measurements should be performed with the above-described probe in order to establish the quenching conditions that can be obtained in existing facilities. For every quenching process the functions: $T_s = f(t)$; $\Phi = f(t)$; $\Phi = f(T_s)$ should be recorded and stored in the computer memory where:

T_s = surface temperature of the probe, °C
t = time, sec
Φ = heat flux at probe surface, MW/m^2

It is essential for each quenching process to describe the operating conditions, including the quenching technique, agitation rate and direction, bath temperature, etc., and store the relevant data together with the above-mentioned functions. Adequate software was developed to establish such a data base provided the probe for making quenching intensity measurements is available. The hardness distribution data obtained by quenching test specimens, as described in the previous paragraph, are also stored in this data base. Such a data base can be developed further by storing data about new quenching conditions and/or steel grades. The data base is the starting point for predicting the hardness distribution using the method explained in the next paragraph. Also, the data base can be used when comparing the quenching intensity with other quenching facilities and/or techniques and for establishing the required quenching conditions.

PREDICTING THE HARDNESS DISTRIBUTION IN ROUND BARS WITH DIFFERENT DIAMETERS

This method of computer-aided prediction of hardness distribution after quenching is valid for bar diameters from 20 to 90 mm.

Figure 4 gives the flow chart of the program, input data, and calculations that must be performed step by step as follows: (See also the stepwise scheme in Figure 5.)

(a) Specify the steel grade and quenching conditions.
(b) Harden a test specimen of the same steel grade by quenching it under specified conditions.
(c) Measure the Rockwell hardness (HRC) across the test specimen cross section as described above.
(d) Input into the computer the hardness values for five characteristic points on the test specimen cross

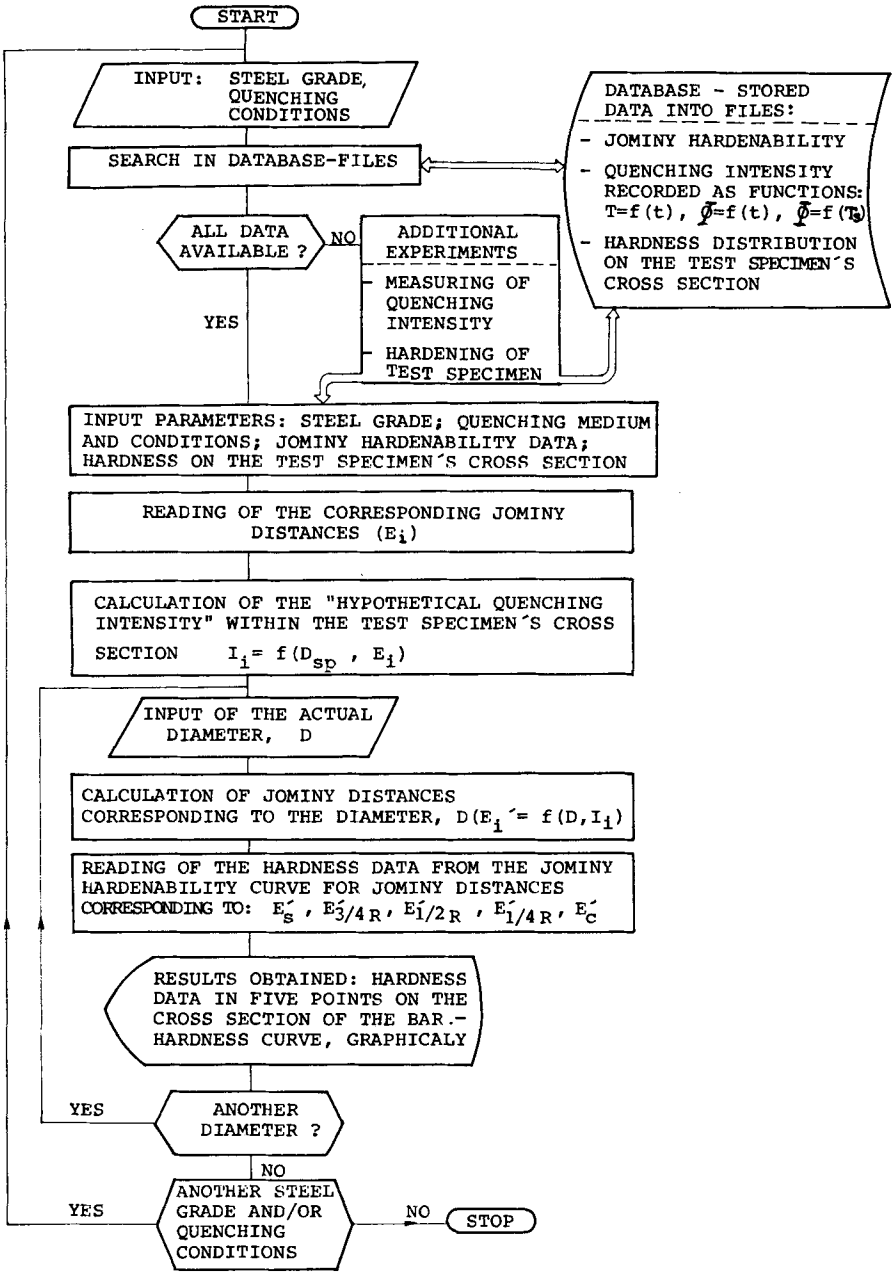

Fig. 4. Flow chart of computer-aided prediction of hardness distribution on quenched round bars' cross sections.

section (S = surface; $^3/_4$R; $^1/_2$R; $^1/_4$R; C = center), and, by means of stored Jominy hardenability data for the relevant steel grade, read the equidistant points on the Jominy curve (E_S; $E_{3/4R}$; $E_{1/2R}$; $E_{1/4R}$; E_C), which have the same hardness as measured at the relevant points on the test specimen cross section.

(e) Calculate the hypothetical quenching intensity I at each of the above-mentioned characteristic points on the test specimen cross section by means of regression equations (3) through (7) based on known values for E_S, $E_{3/4R}$, $E_{1/2R}$, $E_{1/4R}$, E_C, and the test specimen diameter D. Equations (3) through (7), which combine the equidistant points on the Jominy curve, the test specimen diameter D, and the hypothetical quenching intensity I, have been derived from the regression analysis of a series of Crafts-Lamont diagrams [5,6].

This analysis is based on the relations from Just [7] for the surface and center of a cylinder that generally can be written as:

$$E_i = A \frac{D^{B_1}}{I^{B_2}} \tag{2}$$

where

E_i = corresponding equidistant point on the Jominy curve

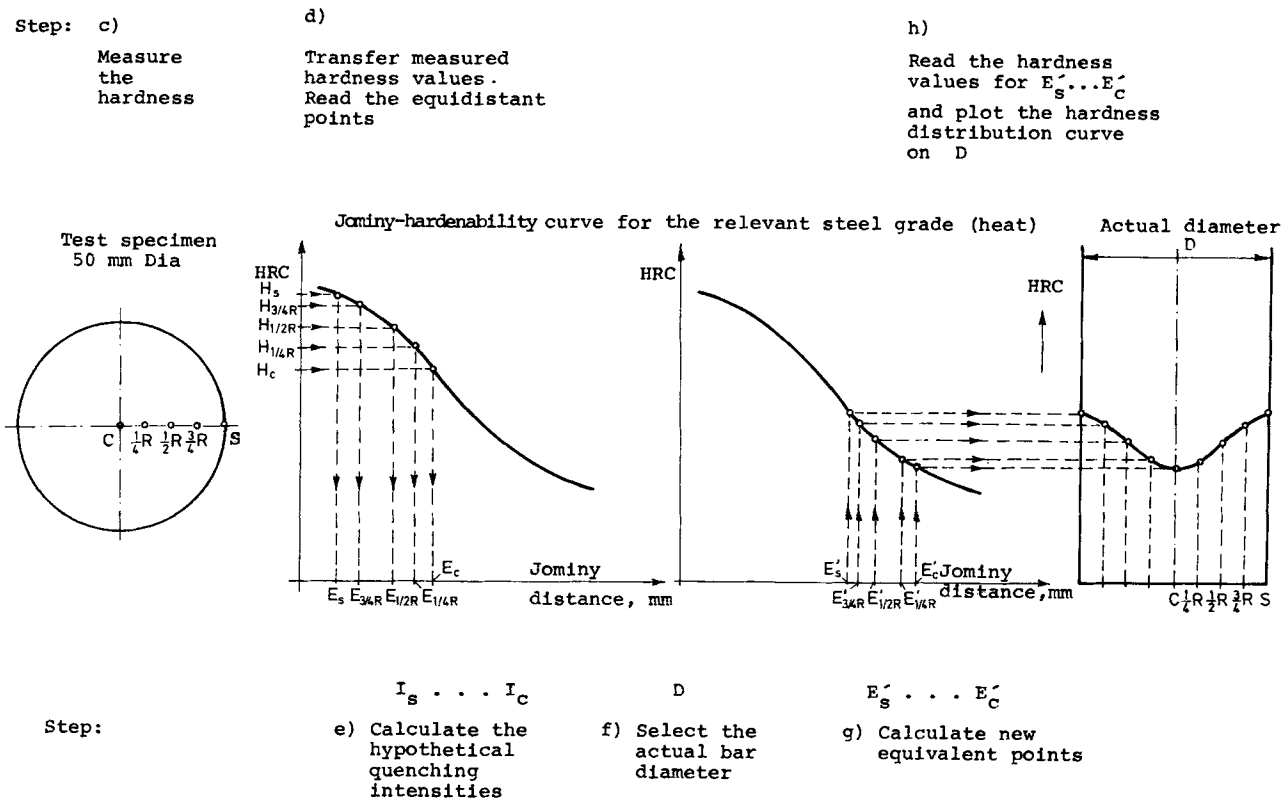

Fig. 5. Stepwise scheme of the process of prediction of the hardness distribution (see text).

A, B_1, B_2 = regression coefficients
D = cylinder (bar) diameter
I = quenching intensity ("H" according to Grossman)

By means of regression analysis, the following relations have been obtained:

$$E_S = \frac{D^{0.718}}{5.11 \times I^{1.28}} \quad \ldots \tag{3}$$

$$E_{3/4R} = \frac{D^{1.05}}{8.62 \times I^{0.668}} \quad \ldots \tag{4}$$

$$E_{1/2R} = \frac{D^{1.16}}{9.45 \times I^{0.51}} \quad \ldots \tag{5}$$

$$E_{1/4R} = \frac{D^{1.14}}{7.7 \times I^{0.44}} \quad \ldots \tag{6}$$

$$E_C = \frac{D^{1.18}}{8.29 \times I^{0.44}} \quad \ldots \tag{7}$$

These equations are valid for $20 < D < 90$ mm, $1 < E < 40$ mm, and $0.2 < I < 2.0$. It is presupposed that at every point of the cylinder cross section there exist different cooling conditions that have been taken into account through the hypothetical quenching intensity I. The value of the hypothetical quenching intensity can be calculated for every specific point from Eqs. (3) through (7). At for the center of the cylinder cross section we obtain:

$$I_C = \left[\frac{D^{1.18}}{8.29 \times E_C}\right]^{2.27} \tag{8}$$

(f) Enter the actual bar diameter D for which the predicted hardness distribution is desired.

(g) Calculate the equidistant Jominy distances (E'_S; $E'_{3/4R}$; $E'_{1/2R}$; $E'_{1/4R}$; E'_C) according to Eqs. (3) to (7) which correspond to the actual bar diameter D and to the calculated quenching intensities: I_S; $I_{3/4R}$; $I_{1/2R}$; $I_{1/4R}$; I_C.

(h) Read the hardness values from the relevant Jominy curve that belong to the calculated Jominy distances: E'_S; $E'_{3/4R}$; $E'_{1/2R}$; $E'_{1/4R}$; E'_C, and plot the hardness distribution curve over the cross section at the chosen actual diameter D.

Figure 6 gives an example of computer-aided prediction of hardness distribution for 30 mm diam and

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PREDICTION OF HARDNESS DISTRIBUTION
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        INPUT DATA:
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 STEEL GRADE:C.4732 (SAE-4140H);B.NR.43111
 QUENCHING CONDITIONS:OIL-UTO-2;20°C;0M/S

   DIAMETER FOR HARDENING,MM:30
   ----------------------------
 RESULTS OF COMPUTER AIDED PREDICTION:
 *************************************

   CALCULATED HARDNESS:
   --------------------
        DIAMETER=30MM

        SURFACE,HRC.......=55.3
        3/4 RADIUS........=54.3
        1/2 RADIUS........=53
        1/4 RADIUS........=51.5
        CENTER............=51.1

 GRAPHIC PRESENTATION(YES=1,NO=0)?1
        ANOTHER DIAMETER (YES=1,NO=0)?:1

   DIAMETER FOR HARDENING,MM:70

        DIAMETER=70MM

        SURFACE,HRC.......=53.1
        3/4 RADIUS........=46.4
        1/2 RADIUS........=40.7
        1/4 RADIUS........=39.6
        CENTER............=39

 GRAPHIC PRESENTATION(YES=1,NO=0)?1
        ANOTHER DIAMETER (YES=1,NO=0)?:0
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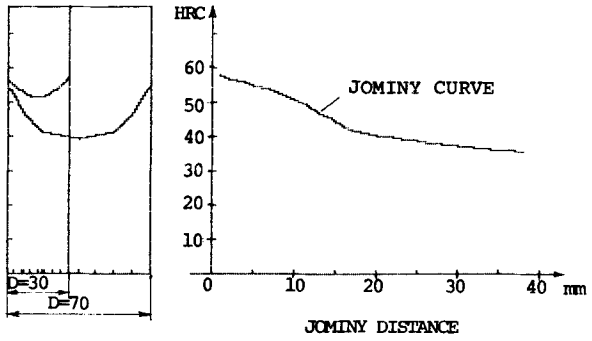


Fig. 6. An example of computer-aided prediction of hardness distribution for quenched round bars of 30 and 70 mm diam steel, grade SAE 4140H.

70 mm diam bars made of SAE 4140H quenched in an oil at 20°C without agitation.

COMPARISON WITH EXPERIMENTALLY OBTAINED RESULTS

Figure 7 gives the comparison of the hardness distribution across round bars measured after experimental quenching and obtained by computer-aided prediction. In this comparison three different steel grades, four different bar diameters, and three different quenching conditions have been used.

In order to ascertain the precision of the hardness distribution prediction, the prediction was, in some cases, additionally performed by the Gerber-Wyss method [8]. In this case, the quenching intensity "H" according to Grossman was established experimentally; for the oil used at 20°C at an agitation rate of 1 m/sec, H = 0.417; for water at 20°C and an agitation rate of 1 m/sec, H = 1.38.

From the examples under numbers 2, 3, 5, and 6 on Figure 7 it can be seen that the computer-aided prediction gives a better fit to the experimentally obtained results.

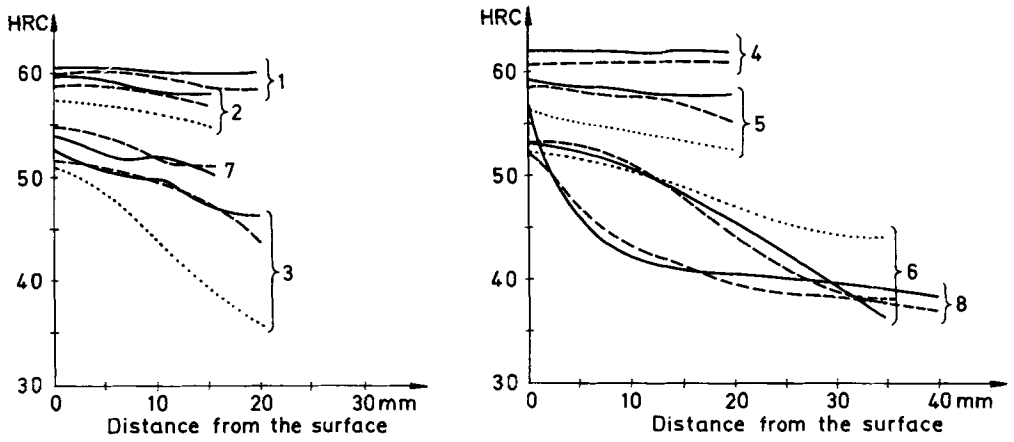
CONCLUSIONS

There is a need for further experiments to determine the applicability and the precision of the proposed method when applied to other steel grades and other quenching conditions. The most important advantages of this method are the following:

(a) By using the Liscic–NANMAC probe, it is possible to measure the quenching intensity in the shop for different quenchants and quenching conditions, and to record and store the data in the form of adequate functions. With this data it is possible to compare the real quenching intensity during the entire quenching process for different quenching facilities, and to reproduce the required quenching intensity independent of time and place. Moreover this probe provides a means of controlling the quenching process by intentionally changing the influential parameters during quenching.

(b) The established data base for steel grades of interest and quenching conditions, complete with the hardness values from test specimens, enables a quick computer search to find the optimum quenching conditions when a certain hardness distribution within a specified bar cross section is required. If, for example, 10 steel grades and 10 different quenching conditions are of interest, then 100 test specimens must be hardened, hardness measurements taken, and the data stored. For every relevant quenching process the quenching intensity also should be measured, recorded, and stored.

By using such a data base one can obtain the predicted hardness distribution in bars having diameters between 20 and 90 mm using any of 10 steel grades and any of 10 different quenching conditions, provided that the surface conditions of bars are equal to those of test specimens. For each specified and stored quenching condition, one can also compare hardness curves on test specimens using steel grades with different hardenabilities.



1. STEEL GRADE: SAE-6150 H, OIL UTO-2, 20 °C, 1 m/s D = 40 mm
2. " " : " " " " D = 30 mm
3. " " : SAE-4135 H, " " " D = 40 mm
4. " " : SAE-6150 H, WATER, 20 °C, 1 m/s D = 40 mm
5. " " : " , OIL UTO-2, " " D = 40 mm
6. " " : SAE-4135 H, WATER, 20 °C, 1 m/s D = 70 mm
7. " " : SAE-4140 H, OIL UTO-2, 20 °C, 0 m/s D = 30 mm
8. " " : SAE-4140 H, " " " D = 80 mm

——— Obtained by experiment

– – – Computer-aided prediction

····· Prediction according to Gerber-Wyss method

Fig. 7. Comparison of the hardness distribution on round bars' sections of different diameters measured after experiments and obtained by computer-aided prediction as well as by prediction according to the Gerber-Wyss method.

Finally, for each steel grade where adequate data have been stored, the influence of specific quenching parameters on the hardness curve of the specimen cross section can be calculated.

Investigations are underway to permit the selection of the best quenching conditions if a certain hardness in the bar cross section must be obtained with a specified steel grade and bar diameter.

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