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ALGORITHM FOR CONTROLING OF QUENCH HARDENING PROCESS OF CONSTRUCTIONAL STEELS

ALGORYTM STEROWANIA PROCESEM HARTOWANIA STALI KONSTRUKCYJNYCH

The computer program "PWD – QUENCH HARDENING" was developed for supporting of quenching process of constructional steel. Using data on the effect of chemical composition of steel on its ideal critical diameter the hardenability parameters are calculated. Program enables to select a quenching media for through hardening of steel bars with given diameter. The data base of 91 grades of constructional steels was prepared.

Opracowano program „PWD – QUENCH HARDENING" do wspomagania procesu hartowania stali konstrukcyjnych. Program umożliwia obliczenie parametrów hartowności stali na podstawie składu chemicznego i wielkości ziarna austenitu, jak również dobór ośrodka chłodzącego, zapewniającego hartowanie na wskroś elementu w kształcie walca o danej średnicy. Opracowano bazę składów chemicznych 91 gatunków stali konstrukcyjnych.

1. Introduction

In heat treatment of steels, in which phase transformations occur, the final microstructure and mechanical properties of the heat treated object depend on the heat treatment parameters: rate of heating to hardening temperature, time of austenitizing and rate of cooling after austenitizing. Therefore the knowledge of these parameters is very important for planning and optimizing of the heat treatment processes. In technological practice these parameters are applied in form of empirical formulae or charts presenting appropriate relationships between required parameters and chemical composition or size of heat treated object. Digitalizing of the graphical data enable to use them in computer programs supporting the heat treatment processes. The greatest change of mechanical properties of steel occur during quenching process and final microstructure after this process depends on the hardenability of steel.

Hardenability of steel is an important factor, which allows an appropriate choice of steel on constructional objects. One of methods for calculation of the hardenability parameters of steel is so called Grossman's method [1]. This method, on the basis of chemical composition of steel and austenite grain size, enables to calculate the ideal critical diameter, D_i, using the empirical relationships which determine the influence of alloying elements and the austenite grain size on the value of D_i. Data on the effects of alloying elements on the hardenability of steel are presented in graphic form in papers [1-4]. Mathematical description of these relationships allows numerical calculation of the D_i. If the value of D_i is known the critical diameter, D_k, can be calculated. For this purpose are used the relationships between D_k and D_i for a specific cooling medium [5, 6]. Cooling medium is characterized by the coefficient of cooling intensity, H. This kind of calculation of hardenability of steel was used in computers programs that are presented in papers [7, 8]. It should be noted that the values of calculated hardenability parameters strongly depend on the data used in calculations. Published data show some differences, so calculations must be verified experimentally by comparison of calculated and experimental values of D_i. The aim of this work was to develop a computer program for supporting of the quench hardening process of constructional steels. The program – on the basis of chemical composition of steel and austenite grain size - calculates the ideal critical diameter, D_i, and selects the quenching medium, which enable through hardening of a bar with specified diameter, D. Additionally the values of austenitizing and cooling times from hardening temperature are calculated.

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2. Description of the computer program

2.1. Idea of the computer program

Algorithm for heat treatment of object in shape of a bar enables to calculate the optimal parameters of quenching, like: hardening temperature, t_H, [°C], austenitization time, τ, [min], coefficient of cooling intensity, H, cooling time, τ_{ch}, [min].

It accepts the preliminary assumptions:

- heat treated object is a bar with a defined diameter, D, and length, l
- the bar is made of low- or medium-carbon low alloy steel.

Input data are divided into two groups:

1. The data entered directly by the user. They include:

- dimensions of the bar (diameter, D and length, l)
- chemical composition or grade of steel according to the standard PN-EN 10020 [9],
- austenite grain size, (Ng).

2. The data presented as a graphical charts describing the relationships between different parameters. Digitizing of these data was carried out by computer processing. In order to determine the values of process parameters, that enable through-hardening of bar the following relationships are used:

a) Hardening temperature, t_H, should be between the lower and upper value of quenching temperature [t_{Hd}, t_{Hg}], where $t_{Hd} = A_{c3} + 30$, $t_{Hg} = A_{c3}+50$. A_{c3} value for definite grade of steel, with a specific carbon content, is usually taken from the equilibrium phase diagram Fe-Fe_3C [10]. In the algorithm, the A_{c3} temperature was described by a polynomial approximation of the relationship between A_{c3} and carbon content, C. This is a simplification that ignores the influence of alloying elements on the thermodynamic equilibrium of existing phases.

b) Time of heating to the hardening temperature, τ [h] – is calculated from the formula [11]:

$$\tau = c_p \cdot \gamma \cdot \frac{R \cdot t_p \left(1 - \sqrt{\frac{\delta t}{t_p}}\right)}{C \cdot \left(T_p/100\right)^4}, \qquad (2.1)$$

where: C – radiation constant, [W/(m^{2}K^4)], c_p – specific heat, [J/kg°C], γ – mass density, [kg/m^3], R – radius of the bar, [m], t_p, T_p – temperature of the furnace, in [°C] and [K], δt – excess of temperature of the furnace, [°C]. It is assumed that austenitizing time at t_H is equal τ.

c) Coefficient of cooling intensity, H – is determined by the empirical relationship between the critical diameter, D_k, and the ideal critical diameter, D_i, from the Grossmann nomogram [5, 6] (Figure 1). The lowest value of H, which enable the through-hardening of the bar is selected using the inequality:

$$D_k \geqslant D. \qquad (2.2)$$

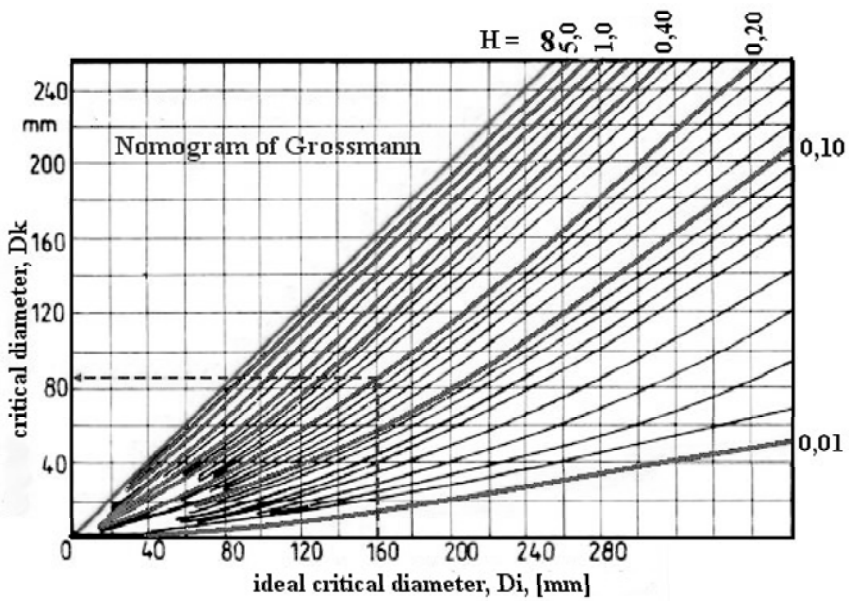


Fig. 1. The relationship between the critical (D_k) and the ideal (D_i) diameter, depending on the coefficient of cooling intensity H [5,6]

d) Cooling medium is closely related to the coefficient of cooling intensity H. Cooling medium is determined by the values of H, the data for typical media are presented in the table 1.

TABLE 1

Values of H for different cooling media [11]

H	cooling medium
(0 – 0,2]	air
(0,2 – 0,3)	oil – motionless of medium
[0,3 – 0,4)	oil – weak agitation of medium
[0,4 – 0,5)	oil – average agitation of medium
[0,5 – 0,8)	oil – strong agitation of medium
[0,8 – 0,9]	oil – very strong agitation of medium
(0,9 – 1,0]	oil – very strong agitation of medium or water – motionless of medium
(1,0 – 1,1]	oil – strong agitation of medium or water – weak agitation of medium
(1,1 – 1,3]	water – weak agitation of medium
(1,3 – 1,5]	water – average agitation of medium
(1,5 – 2,0]	water – strong agitation of medium
2,0	aqueous solution of NaCl – motionless of medium
(2,0 – 2,2]	aqueous solution of NaCl – weak agitation of medium
(2,2 – 4,0)	aqueous solution of NaCl – average agitation of medium
4,0	aqueous solution of NaCl – strong agitation of medium
(4,0 – 5,0]	aqueous solution of NaCl – very strong agitation of medium

e) Time of cooling, τ_{ch}, [s] depends on the cooling medium;

- for air [12]:

$$\tau_{ch1} = \frac{G \cdot c_p}{10^4 \cdot \alpha \cdot s} \ln\left(\frac{t_{sr} - t_{II}}{t_{sr} - t_c}\right), \tag{2.3}$$

- for oil [11]:

$$\tau_{ch2} = \frac{t_H}{7,925} \cdot \left(\frac{w}{s}\right)^{1,37}, \tag{2.4}$$

- for water [11]:

$$\tau_{ch3} = \frac{t_H}{10,01} \cdot \left(\frac{w}{s}\right)^{1,78}, \tag{2.5}$$

- for aqueous solution of NaCl [11]

$$\tau_{ch4} = \frac{t_H}{9,80} \cdot \left(\frac{w}{s}\right)^{1,84}, \tag{2.6}$$

where: G – mass of the object, [kg], α – heat transfer coefficient, [W/m^2°C], s – surface of the object, [cm^2], t_{sr} – medium temperature, t_c – final temperature, w – volume of the object, [cm^3].

2.2. Structure of the algorithm

Algorithm for control of the quenching process of constructional steels contains two main parts:

1. Block of pre-processing graphical information – BPIG (Figure 2a).
2. Algorithm for supporting the decision in the determination of hardening process parameters – PWD *QUENCH HARDENING* (Figure 2b).

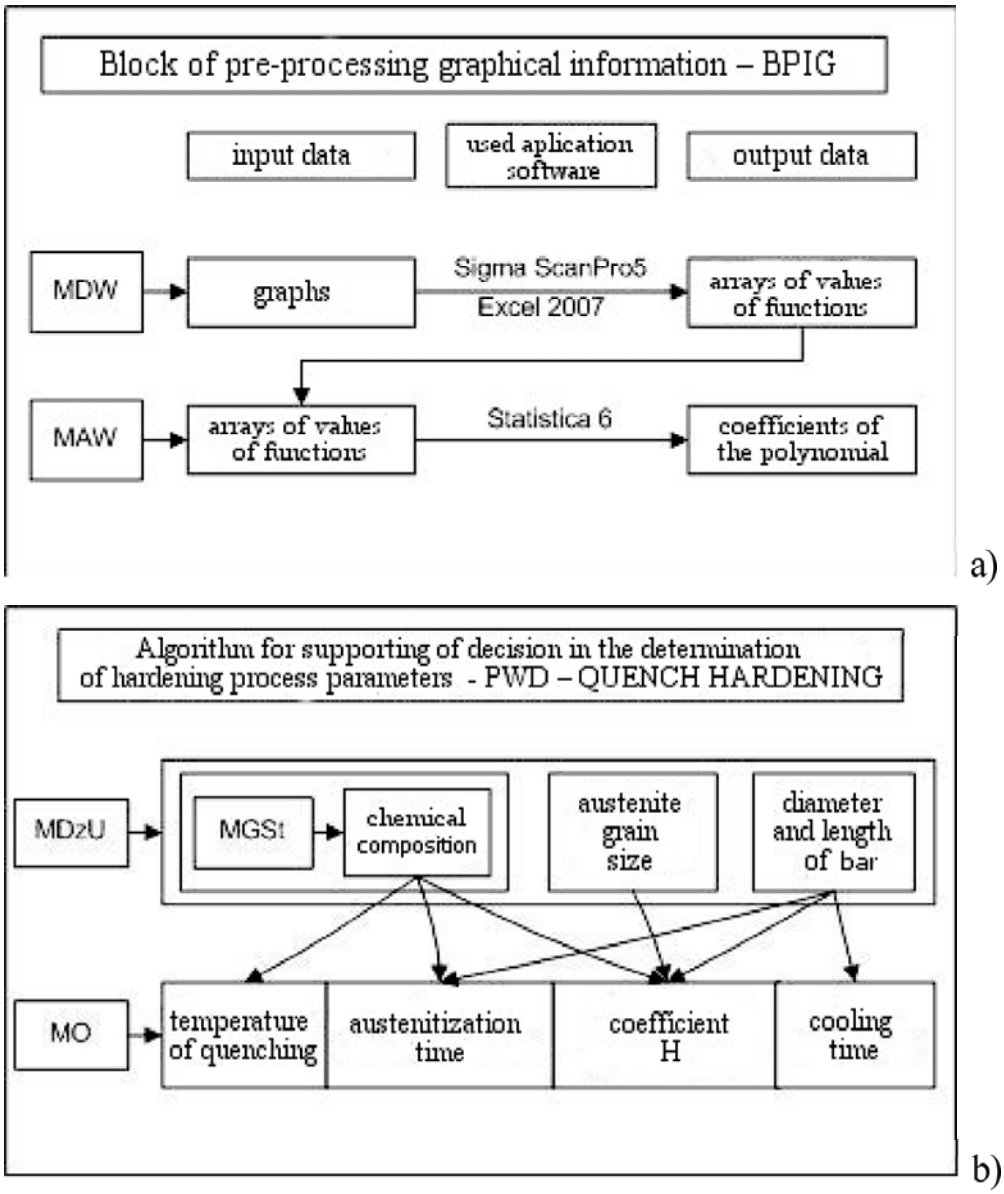


Fig. 2. Construction of algorithm, a) Block of pre-processing graphical information – "BPIG", b) block "PWD – QUENCH HARDENING"

The block "BPIG"

Some relationships between hardening and heat treated parameters are given in the form of graphs in the literature. These relationships are an important source of information for the created algorithm, therefore it was necessary to process the information from the graphic form to arithmetic expressions, using block BPIG.

There are two modules in the block of pre-processing graphical information – BPIG (fig. 2a).

- Module of digitization graphs – MDW.
- Module of polynomial approximation – MAW.

MDW module – input data in form of graphs were digitalized using computer program SigmaScan Pro [13]. Digitalization was carried out for relationships between: A_{c3} and carbon content, C, – $A_{c3} = f(C)$ [10], heat transfer coefficient α (cooling in air) and temperature, $t - \alpha = f(t)$ [14], critical diameter, D_k, and D_i for different intensity cooling coefficient, $H - D_k = f(D_i, H)$ [5, 6]. Mathematical description by the polynomial approximation of the relationships was carried out using computer programs MS Excel and Statistica 6 [15].

For specific values of H the relationship between D_k and D_i was approximated by forth order polynomial:

$$D_k = a_0 + a_1 D_i + a_2 D_i^2 + a_3 D_i^3 + a_4^4. \qquad (2.7)$$

Calculated coefficient a_i for different values of H are given in table 2.

TABLE 2

Coefficients $a_0, ..., a_4$ of polynomials approximation $D_k = f(D_i; H)$ for different values of coefficients of cooling intensity, H.

H	a_0	a_1	a_2x10^3	a_3x10^5	a_4x10^8	H	a_0	a_1	a_2x10^3	a_3x10^5	a_4x10^8
0,01	0,55	0,013	0,60557	-0,069388	-0,0026576	0,18	0,11	0,041	4,39145	-1,182333	1,27637577
0,02	0,39	0,029	1,02856	-0,272303	0,2942025	0,20	-0,01	0,040	4,81749	-1,394158	6,00365859
0,03	0,22	0,037	1,33769	-0,481892	0,74307435	0,25	-0,16	0,081	4,87152	-1,371259	1,52677326
0,04	-0,35	0,105	0,31432	0,098679	-0,06759149	0,30	-0,81	0,174	4,37082	-1,179187	1,2690338
0,05	-0,21	0,104	0,34336	0,270358	-0,44463777	0,35	-0,79	0,188	4,5162	-1,179374	1,17850986
0,06	-0,02	0,088	0,77447	0,194426	-0,40001216	0,40	-1,23	0,239	4,47606	-1,204526	1,20261066
0,07	0,03	0,084	1,0719	0,111991	-0,3172376	0,50	-0,46	0,247	5,13232	-1,59599	1,83687097
0,08	0,07	0,087	1,18737	0,13268	-0,3972244	0,60	-0,08	0,334	4,50049	-1,358414	1,50334989
0,09	0,45	0,063	1,67598	-0,007876	-0,28565709	0,80	-0,32	0,407	4,79341	-1,713639	2,2007807
0,10	0,50	0,059	1,95542	-0,101506	-0,17949237	1,00	0,08	0,501	4,15407	-1,520619	1,9879424
0,12	0,93	0,010	3,12698	-0,594257	0,45560193	2,00	-0,44	0,635	3,85547	-1,72892	2,68025555
0,14	0,73	-0,006	4,21884	-1,104774	1,14302059	5,00	-0,23	0,742	3,14276	-1,469654	2,33487864
0,16	0,21	0,029	4,20707	-1,10662	1,1593098	∞	0	1	0	0	0

The polynomial relationships between temperature A_{c3}, [°C], and carbon content, C, [mass %] has the form:

$$A_{c3} = 912 - 519.31C + 589.47C^2 - 297.8C^3. \quad (2.8)$$

The relationship between heat transfer coefficient α, [W/m^2 °C], and temperature t, [°C], for cooling in the air in a polynomial representation:

$$\alpha = 11,512 - 0,007025t + 0,000149t^2. \quad (2.9)$$

The block "PWD – QUENCH HARDENING"

The algorithm for supporting of hardening process of constructional steels, implemented in block "PWD – QUENCH HARDENING", is built on the following modules, (Fig. 2b):

- module of communication with users – MDzU,
  - module of cooperation with the database gatunki_stali.txt – MGSt,
- module of calculation – MO.

MO – module of calculation is the most important component of the created algorithm. It calculates the basic parameters (t_H, τ, H, t_{ch}), controlling the quench hardening process. Block diagram of the calculations is shown in Figure 3.

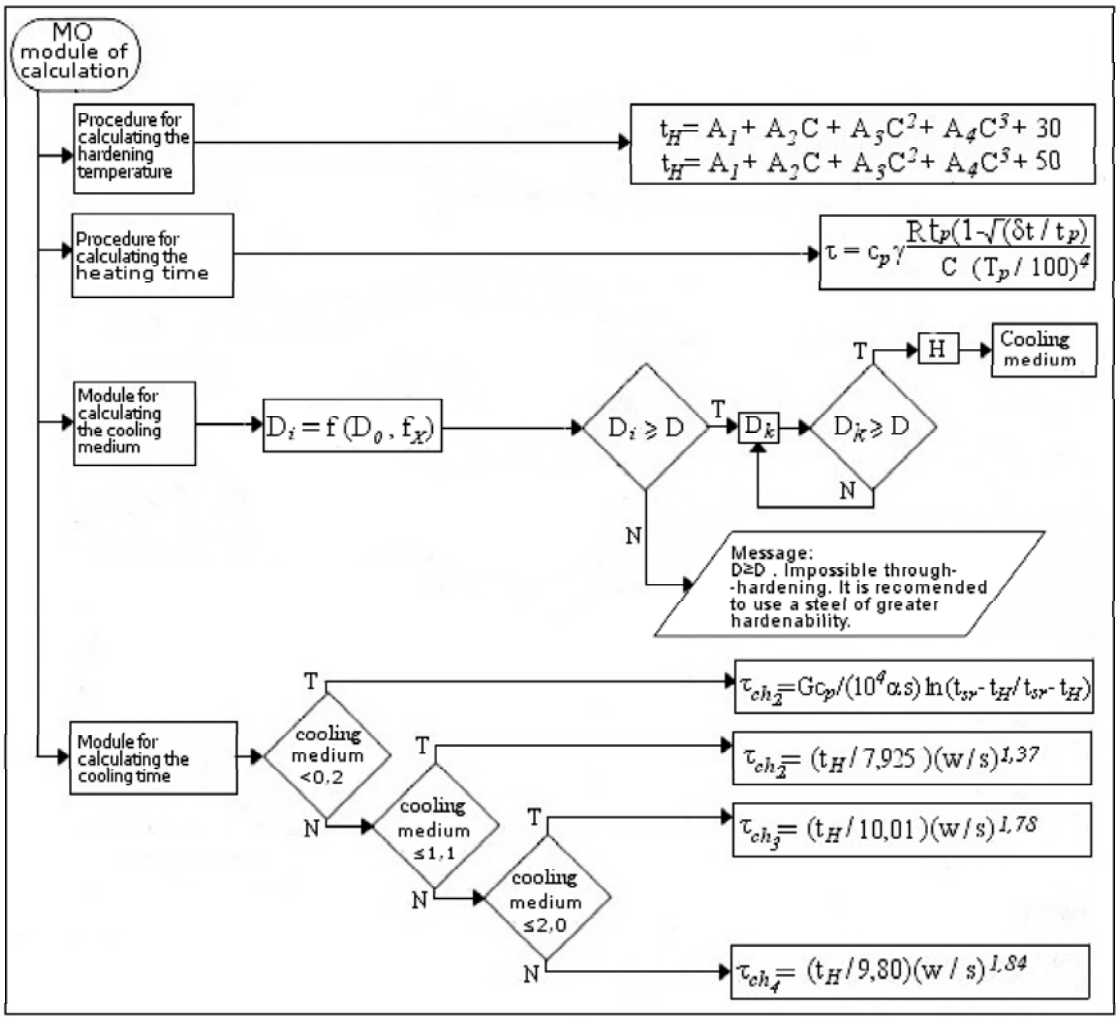


Fig. 3. Block diagram of the computational module

To run the module we must first enter the input data such as:

- chemical composition or grade of steel specified by the standard PN – EN 10020 [9],
- austenite grain size, Ng,
- diameter, D, and length, l, of the bar.

To prevent a situation when exact chemical composition of quenching bar is not known, a module MGSt was created (used by the module MDzU). This module is responsible for working with a database that contains the chemical composition of a set of constructional steels [16].

2.3. Implementation of the algorithm

Algorithm for control of quenching process of constructional steels has been implemented in C++ using the software Borland Builder 6 [17]. The computer program was called PWD – QUENCH HARDENING. The program can run on any computer with Microsoft Windows operating system.

Created application include graphic utility interface which helps its user enter data (Figure 4). For the algorithm the most important information is the chemical composition of steel (in mass %: C, Mn, Si, Ni, Mo, Cr, P, S, Cu). Information on chemical composition of steel can be input directly or by choosing the grade of steel (if exact composition is not available). In this last case is possible to use the menu scroll box.

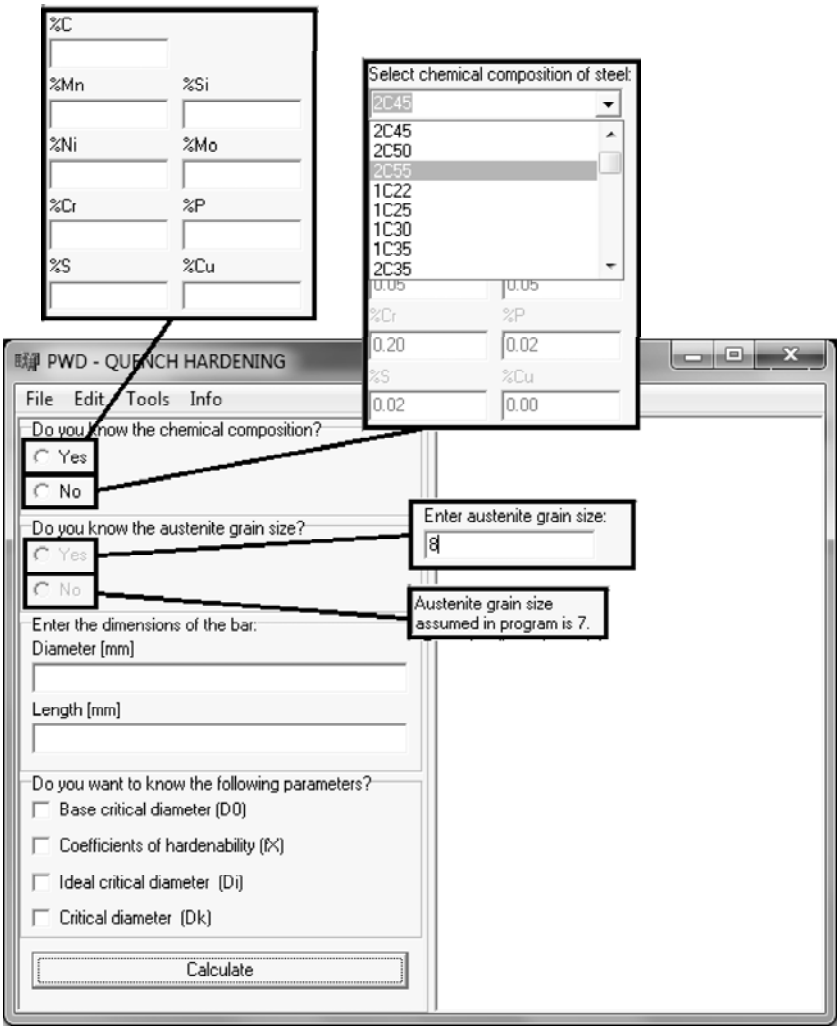
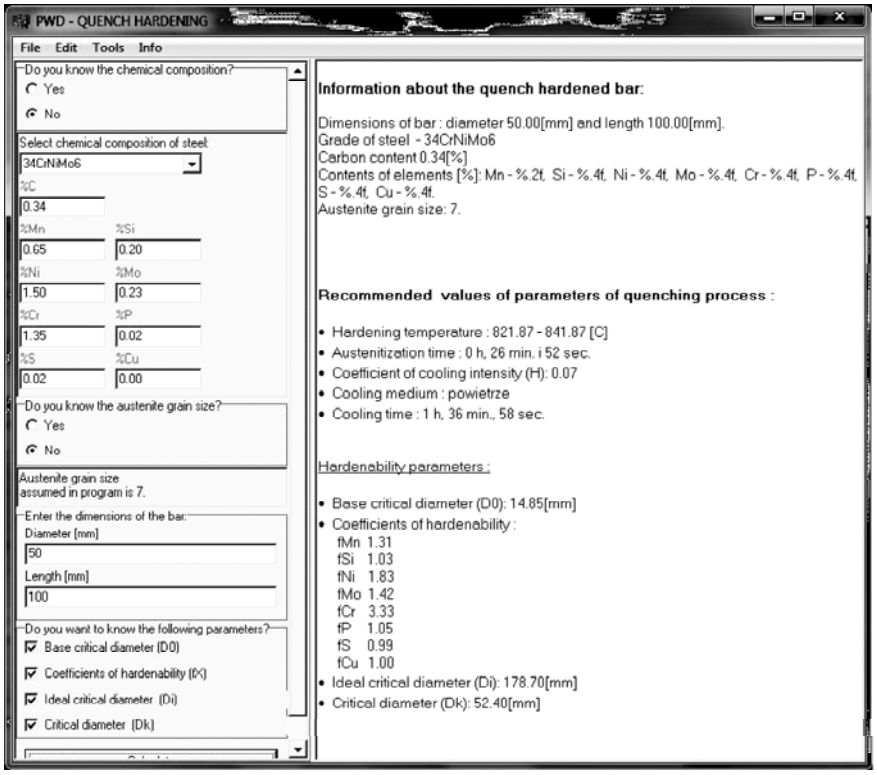


Fig. 4. Module of communication – MDzU

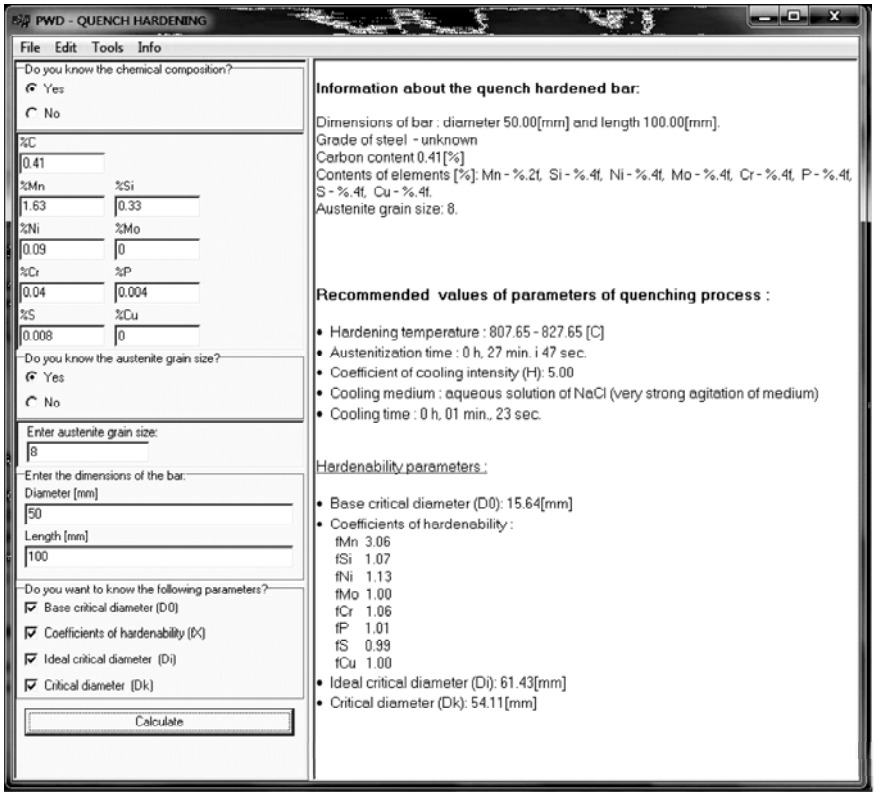
Steel grade selection is carried out using developed database. The database contains chemical compositions of selected grades of low- or medium-carbon steels, low alloy. The database is an integral part of the program but was created in a separate file named gatunki_stali.txt. The file was created on the basis of information contained in [16]. The file contains 91 records (91 grades of steel). Each record is composed of 10 fields. The first field contains the name of the steel grade specified by the standard PN – EN 10020. This field is a key, which is the identifier of the record. Subsequent fields contain the average contents of elements such as: C, Mn, Si, Ni, Mo, Cr, P, S, Cu. Data typically provides the minimum and maximum content of the element in steel, therefore in calculation the average element content is taken. Calculations for the average content of elements are less accurate compare to the exact contents of the elements in steel.

Another important input data is the austenite grain size. For low carbon steel, this variable takes integer values in the range 4 – 10 and for medium carbon steel the values in the range 1 – 12, [2,3]. If austenite grain size is out of this range it is assumed as low or high limit of the range (which is closer). On request the program may display results of intermediate calculation.

The developed program is able to react to unforeseen situations, for example when the user does not enter the total input data or enter incorrect data. In this case, program displays a suitable message. Examples of application of the program for hardenability parameters for two steels (34CrNiMo6 and 40Mn6) are presented in fig. 5.



a)



b)

Fig. 5. Examples of application of the computer program "PWD – QUENCH HARDENING", left panel – input data, right panel – results of the algorithm calculation, a) steel – 34CrNiMo6, b) – steel 40 Mn6

Calculation of the parameters starts after entering all the data and pressing button "Calculate". The results are displayed in the right panel of the dialog box. First, the panel displays information about the quench hardened bar. Then displays the results of the algorithm computation. Analyzed steels have a different hardenability related to their chemical composition. The calculated values of D_i are 178,7 and 61,4 mm for steel 34CrNiMo6 and 40Mn6 respectively. For through hardening of bars of diameter 50 mm and length 100 mm made from these steels different quenching media are required: the bar made of 34CrNiMo6 steel can be cooled in air whilst the bar made of 40Mn6 steel has to be quenched in NaCl water solution.

3. Concluding remarks

In paper the developed computer program "PWD – QUENCH HARDENING" is presented. This program enable to calculate the parameters of quenching process of steel object with shape of a bar with known dimensions and chemical composition. Using the data of chemical composition and austenite grain size the ideal critical diameter, D_i, is calculated and cooling medium enabling through – hardening of the bar is selected. This program can be an useful tool supporting planning and optimizing of the heat treatment processes in steel industry. Also can be used for education in materials engineering.

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