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Heat treatment influence on mechanical properties of structural steels for quenching and tempering

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Analysis and modelling

ABSTRACT

Purpose: This paper introduces analysis results of heat treatment conditions influence on mechanical properties of alloy structural steels for quenching and tempering.
Design/methodology/approach: Investigations were performed in virtual environment with use of materials science virtual laboratory. Virtual investigations results were verified in real investigative laboratory.
Findings: Performed verification investigations presented in this paper on selected mechanical properties modelling examples of structural steels clearly show the correctness of the developed computational model of structural steel and confirm the possibility of its use in the industrial production, both to predict the properties, as well as to design new types of steel.
Practical implications: Results of virtual examinations can be presented as raw data or influence charts
Originality/value: The effectiveness of the virtual environment application for the prediction, simulation and modelling of the steel properties is presented
Keywords: Computational material science; Materials science virtual laboratory; Structural steel; Virtual investigations

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1. Introduction

Development of virtual tools, which are simulating the investigative equipment and simulating the research methodology, can serve as a basis for combining aspects of laboratory research, simulation, measurement, and education. Application of these tools will allow the transfer of research and teaching procedures from real laboratory to virtual environment. This will increase the number of experiments conducted in virtual environment and thus, it will increase the efficiency of such researches [1]. Modelling of structural steels mechanical properties is valuable for steel designers and manufacturers, because it is associated with financial benefits, when expensive and time-consuming researches are reduced to necessary minimum [2,3].

On the basis of experimental studies of mechanical properties with use of artificial neural networks a numerical model for structural steels has been developed. Developed intelligent structural steel model allows determining the mechanical properties based on the characteristic descriptors of steel. The described model allows the simultaneous prediction and modelling of eight mechanical properties of structural steels.

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Possible is also determination of steel's chemical composition, treatment conditions and geometric dimensions based on the mechanical properties of steel. Developed computational structural steel model has a very wide range of variability of input. It can be used to predict the steel's properties after heat treatment carried out under different conditions [4-6].

The development of computational methods and computer simulations makes possible the replacement of the traditional laboratories in favour of the virtual laboratory. Development of virtual tools, simulating operation the research equipment and simulating the research methodology, can serve as a basis for combining aspects of laboratory research, simulation, measurement, and education [7-10]. To take full advantage of developed model an authorship computer-aided modelling system was designed. Materials science virtual laboratory is a tool developed at the Institute of Engineering Materials and Biomaterials, used for prediction and modelling of complex mechanical properties of alloyed and unalloyed structural steels. This laboratory also allows visualization of the results, simulations and predictions made with the use of developed computational structural steel model [7,11].

2. Material and method

In order to experimental verification of developed computational model functionality in this paper, consecutively two aspects of researches were selected. first, experimental verification of model's computation correctness was performed in order to answer the question whether it is possible to perform virtual tests using only material developed a virtual environment. Next, virtual material testing was performed to determine the influence of heat treatment conditions on structural steels mechanical properties.

Structural steels are the most often produced steel species in the Polish steel industry. They are delivered to the customer as the semi-manufactured or finished products in the form of rods, wires, sections, sheet metals and pipes. Examinations were focused only on the long products in the figure of rods with round, square and rectangular section to the dimension from 20 mm to 220 mm. These products are the most often produced shapes and in the largest dimension assortment [12]. Structural Steels are used in many applications, because they combining good mechanical properties with low price. There are produced in many grades. The uses are various including civil and industrial engineering [13].

Investigations was performed with use of samples made from steel for quenching, tempering and surface hardening in accordance with withdrawn, but still used in industry PN/89 H-84030-04 standard. Designation and chemical composition are presented in Table 1. Conditions of heat treatment and the rod's shape and diameter (or size) are presented in Table 2.

Table 1.
Chemical composition of selected alloy steels

Steel grade	C	Mn	Si	P	S	Cr	Ni	Mo	Ti	Cu	Al
18H2N2	0.19	0.69	0.3	0.012	0.009	1.97	1.82	0.3	0.031	0.056	0.004
20HGSA	0.19	0.99	0.9	0.025	0.025	0.95	0.45	0.09	0.017	0.029	0.023
30HN2	0.29	0.44	0.28	0.018	0.001	0.7	2.05	0.26	0.004	0.12	0.044
36HNM	0.32	0.4	0.17	0.035	0.035	1.3	1.7	0.25	0.001	0.14	0.012
40HNMA	0.41	0.63	0.24	0.015	0.006	0.97	0.9	0.19	0.032	0.21	0.016

Table 2.
Shape and heat treatment conditions of selected alloy steels

Steel grade	Quenching			Tempering			Diameter
	Temperature [°C]	Time [min]	Cooling medium	Temperature [°C]	Time [min]	Cooling medium	
18H2N2	860	30	water	480	30	air	Φ100
20HGSA	880	15	oil	500	15	air	Φ80
30HN2	860	50	water	680	15	air	□110
36HNM	850	20	oil	630	40	air	Φ90
40HNMA	840	45	water	560	20	air	□110

Material was manufactured in electric arc furnaces with devices for steel vacuum degassing (VAD). The material was supplied in the form of heat and plastic treated forged round rods. From these rods, material samples of steel materials were taken. To minimize the possibility of errors materials research were performed in the same way and using the same equipment, which has been used in computational, model obtainment. Due to the large number of investigation results for the presentation in this paper five grades of structural steels were selected.

3. Results and discussion

In aim of modelling and properties prediction, material descriptors, such as chemical composition, heat treatment, plastic treatment and geometric parameters were inputted to material science virtual laboratory. All data were saved in files, which are representation for real material samples in the virtual world.

Results of material investigations obtained with the use the materials science virtual laboratory were compared with the results of investigations conducted in a real laboratory and introduced in Table 3. The chemical composition of steel grades computed in virtual environment was compared with chemical composition of steel grades read from the PN standard. It was found that the concentration of the chemical elements for steel grades computed virtual environment were within the corresponding concentration ranges of real steel. The differences in the marking of steel grades results from the difference in the signs caused by the withdrawal from the use of Polish standards and replace it with the European standard PN-EN 10083-3:2008. In addition, differences between measured and calculated values of the mechanical properties are very small, and any of the cases did not exceed error values of artificial neural networks. In addition, all test results are consistent with the values ranges of mechanical properties located in the standard.

After the verification investigation and confirmation that the virtual environment can be successfully used for research purposes, an analysis how strong influence on mechanical properties has the change of the heat treatment conditions. Virtual researches of the temperature and time of quenching and tempering influence on mechanical properties were performed. For researches, virtual files, which are representing the sample material in a virtual environment, were used. These files were created during the comparative research.

With the use of materials science virtual laboratory relationship graphs between mechanical properties and the selected heat treatment condition that describes the steel was obtained. The ranges heat treatment was selected above and below the base value. The aim of this was to show how strong the influence is by value increase or decrease of selected treatment condition on selected mechanical property of examined steels. The ranges are presented in Table 4.

Selected graphs are shown in Figures 1-10. Complete result set obtained during this analysis is presented in [7]. Calculated values of yield stress $R_{0.2}$, tensile strength R_m, relative elongation A_5 and relative area reduction Z are marked with a single line. The value ranges of impact resistance KCU2 and hardness HB are marked between two lines indicating the minimum and maximum value.

Table 3.
Comparison between measured and predicted mechanical properties of selected alloy steels

Property	Measured	Predicted	Measured	Predicted	Measured	Predicted
Material	18H2N2	18CrNi8	20HGSA	21Mn6	30HN2	30CrNi9
$R_{0.2}$ [MPa]	1025	1017	906	909	1054	1056
R_m [MPa]	1349	1347	1077	1073	1224	1230
A_5 [%]	18.1	17.9	16.0	16.0	19.6	21.8
Z [%]	62.3	62.2	58.3	58.4	59.8	61.8
KCU2 [J/cm^2]	121-144	117-144	155-177	154-183	157-172	159-184
HB	342-365	320-354	300-310	305-313	350-366	353-362
Material			36HNM	34CrNiMo6	40HNMA	42CrMo4
$R_{0.2}$ [MPa]			1130	1136	911	906
R_m [MPa]			1160	1155	1156	1193
A_5 [%]			18.0	18.1	15.8	15.9
Z [%]			50.1	50.0	56.9	56.3
KCU2 [J/cm^2]			10-110	104-114	154-195	144-176
HB			370-377	373-380	310-325	317-324

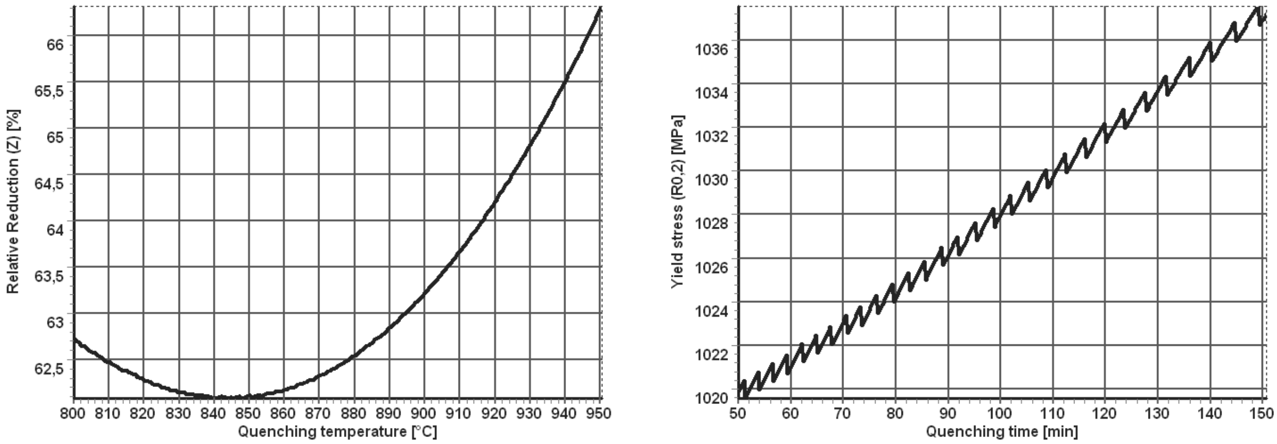

Fig. 1. Influence of quenching temperature on relative area reduction and quenching time on yield stress of 18H2N2 steel

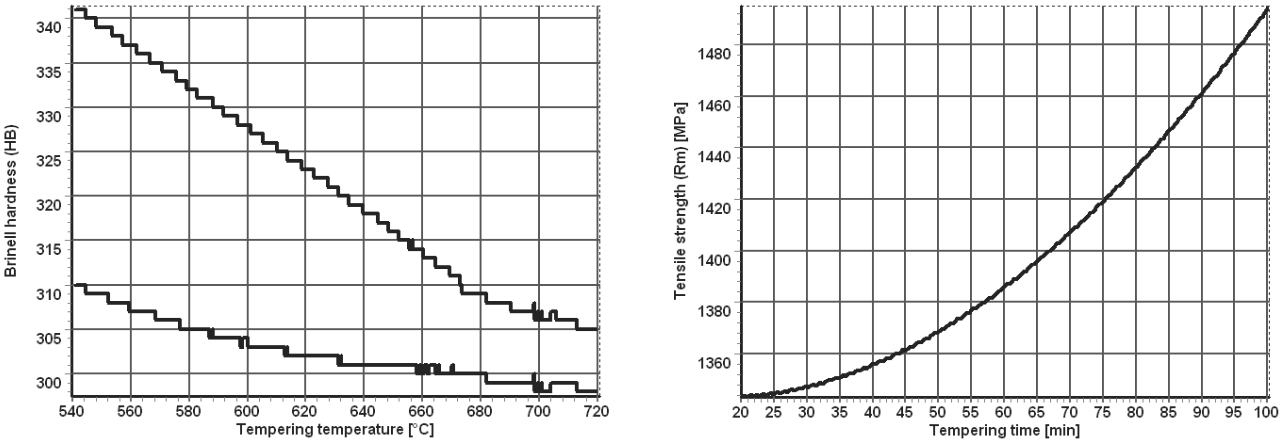

Fig. 2. Influence of tempering temperature on Brinell hardness and tempering time on tensile strength of 18H2N2 steel

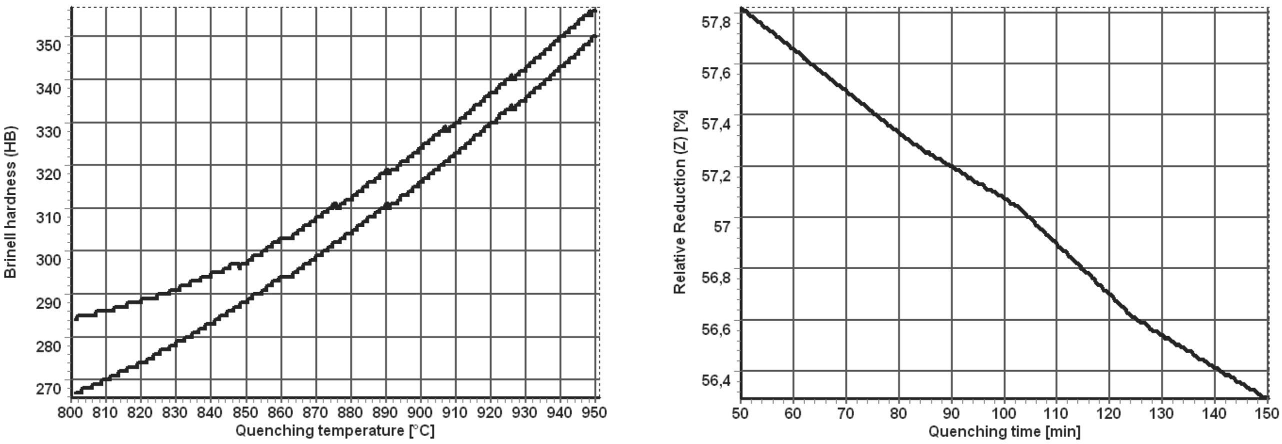

Fig. 3. Influence of quenching temperature on Brinell hardness and quenching time on relative area reduction of 20HGSA steel

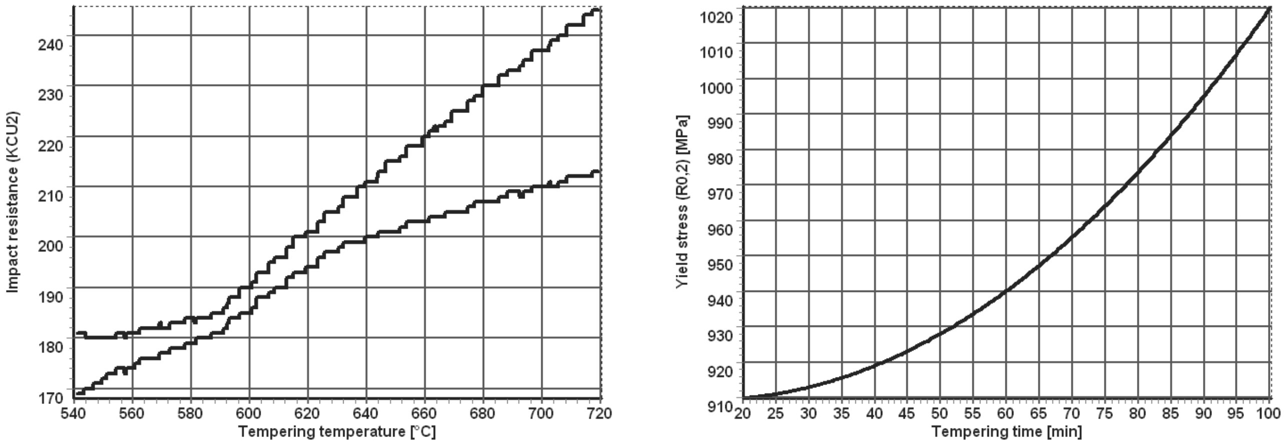

Fig. 4. Influence of tempering temperature on impact resistance and tempering time on yield stress of 20HGSA steel

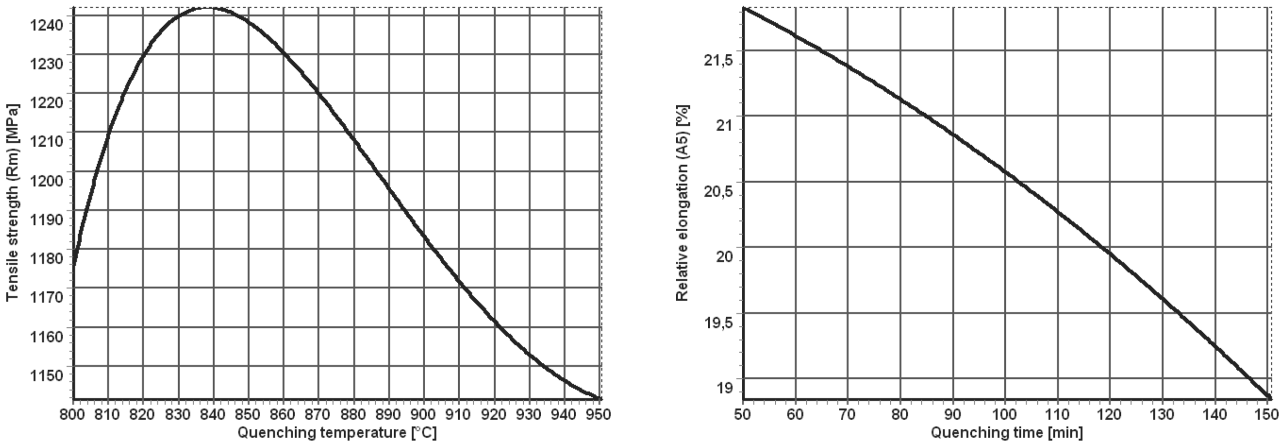

Fig. 5. Influence of quenching temperature on tensile strength and quenching time on relative elongation of 30HN2 steel

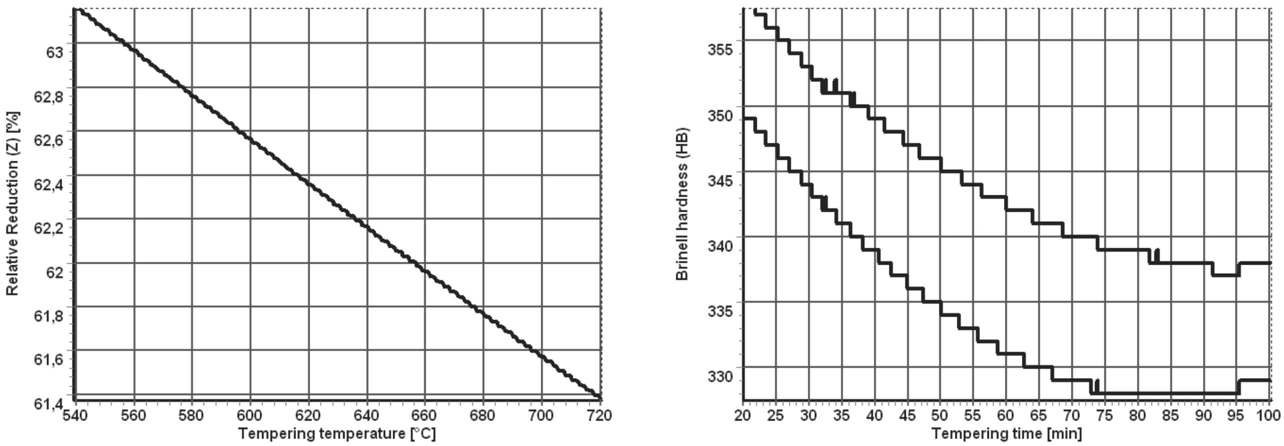

Fig. 6. Influence of tempering temperature on relative area reduction and tempering time on Brinell hardness of 30HN2 steel

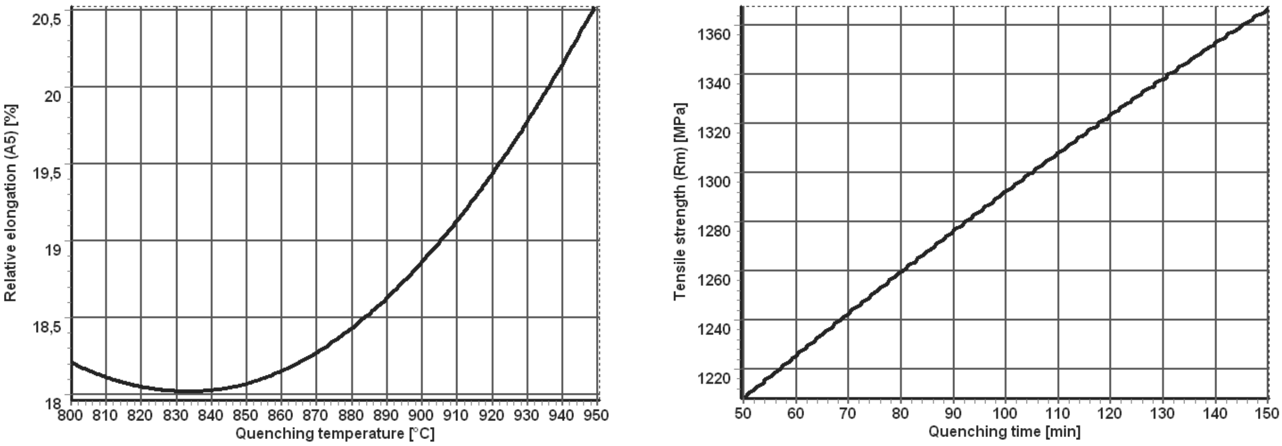

Fig. 7. Influence of quenching temperature on relative elongation and quenching time on tensile strength of 36HNM steel

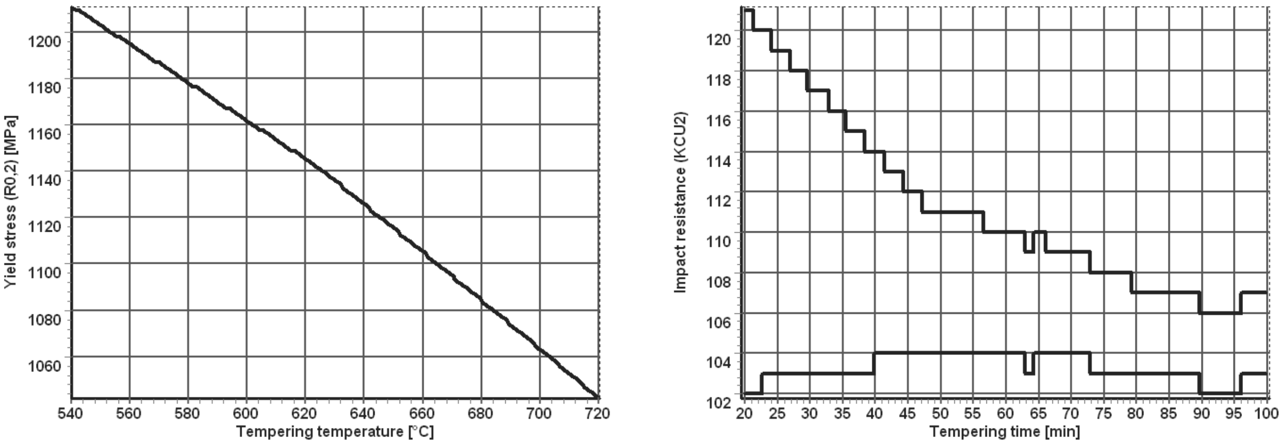

Fig. 8. Influence of tempering temperature on yield stress reduction and tempering time on impact resistance of 36HNM steel

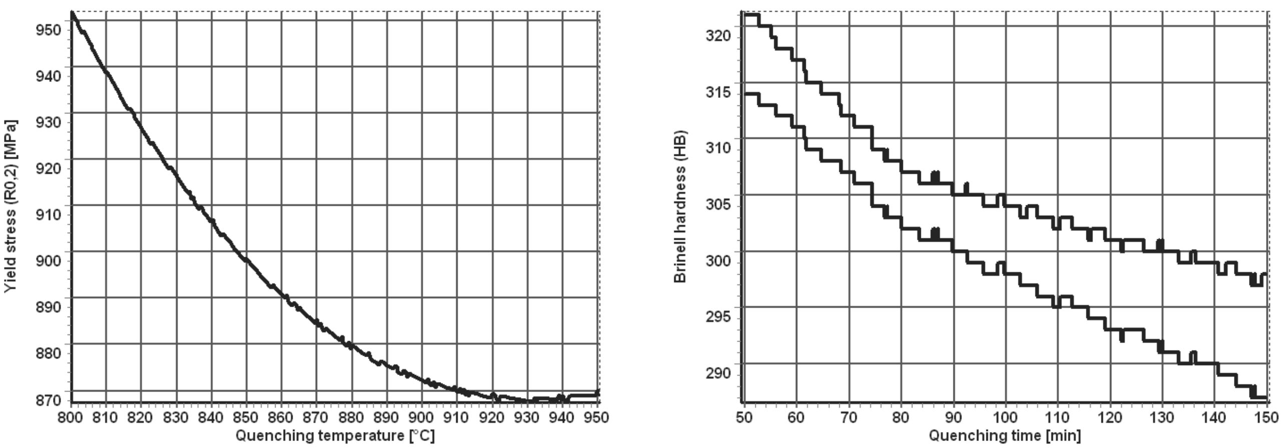

Fig. 9. Influence of quenching temperature on yield stress and quenching time on Brinell hardness of 40HNMA steel

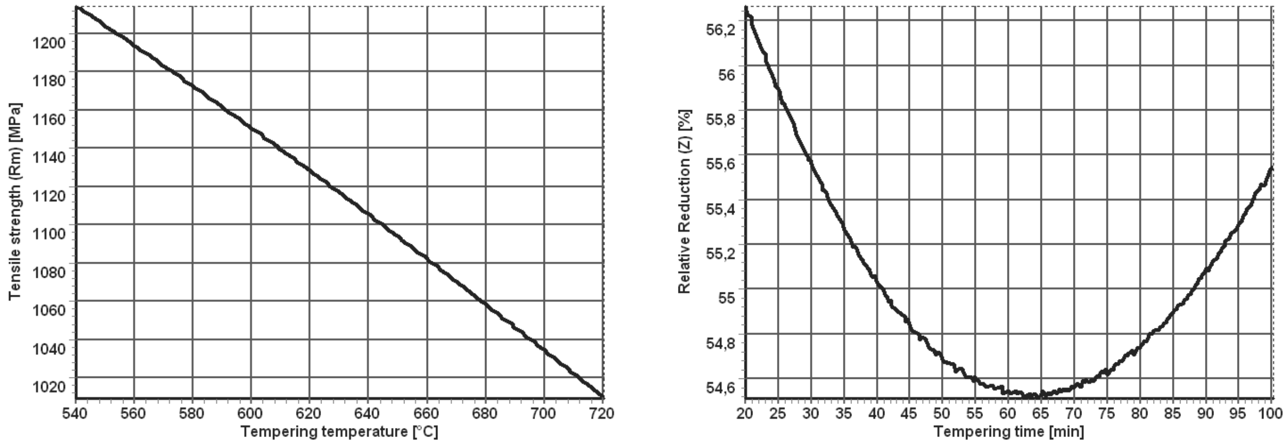

Fig. 10. Influence of tempering temperature on tensile strength and tempering time on relative area reduction of 40HNMA steel

Table 4.
Heat treatment condition ranges used for influence graphs preparation

heat treatment condition	minimum	maximum
quenching temperature [°C]	800	950
quenching time [min]	50	150
tempering temperature [°C]	540	720
tempering time [min]	20	100

4. Conclusions

The correctness of the construction and operation of materials science virtual laboratory in the range of the heat treatment conditions modelling has been fully verified by the verification investigations consisting in a comparison of results obtained by numerical experiments performed only in a virtual environment with the results of real investigations conducted in a real material science laboratory. Performed verification investigations presented in this paper on selected mechanical properties modelling examples of structural steels clearly show the correctness of the developed computational model of structural steel and confirm the possibility of its use in the industrial production, both to predict the properties, as well as to design new types of steel. Correct results were obtained for both the comparison of model results with experimental results as well as for comparison with results taken from existing standards.

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