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Application of neural networks to predict austenite grain size

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The mechanical properties of finished product after plastic working are influenced by many factors. The most important of them include:
1. the method of heating up the material for the hot plastic working process,
2. the technology of plastic working, and
3. cooling after plastic working.

Phenomena occurring during heating and soaking are important as they prepare the material for changes that take place during the deformation and cooling of product. The time and temperature of steel heating determine the chemical composition of the austenite. An excessively grown austenite grain cannot be reduced in size by plastic working, which, as a consequence, leads to a decrease in mechanical properties.

There are mathematical models based on classical relationships, that serve for the determination of the effect of heating conditions on austenite grain size. All these require, however, a lot of complex laboratory tests, and their industrial application for the on-line prediction of austenite grain size is not practicable due to the long time of computations.

An approach that has been more and more widely applied in the model studies of plastic-and-thermal working processes is the use of artificial neural networks for predicting the structure or properties of finished product. The primary advantage of this method is that the development of the model can in most cases be reduced to the analysis of a set of measurement data which are often stored in corporate databases, whereas process parameters are generally physical quantities that can be easily measured or calculated.
The article will present the preliminary results of the attempts of creating a mathematical model based on artificial neural networks to be used for predicting the austenite grain size of C15 steel.

1. PURPOSE AND SCOPE OF STUDIES

The mechanical properties of steel depend on the size of ferrite grains and the parameters describing the pearlitic structure, which form from the austenite. The larger austenite grains, the larger ferrite grains generally form. As an austenite grain grows only during heating, the final size of the grain is determined by the highest temperature of heating the steel (after the formation of the austenitic structure) and the soaking time [1].

Above the temperature A_1, austenite occurs, which is fine-grained directly after the completion of the transformation. Further increase in temperature and the elongation of the austenitization time promote the growth of grains. Cooling down of the fine-grained austenite

leads to the formation of a ferritic-pearlitic structure composed of small clusters of pearlite, whereas from the grown-grained austenite a coarse-grained ferritic-pearlitic structure will form. For the determination of austenite grain size, the following relationship is most often the used:

$$D(t)^{\frac{1}{P}} - D(0)^{\frac{1}{P}} = kt \exp\left(\frac{-Q_g}{RT}\right) \tag{1}$$

where:
D(t) – average size grain after time *t*
D(0) – initial grain size,
p – exponent,
k – kinetic constant,
Qg –activation energy.

The accuracy of such a model is dependent on long-lasting studies aimed at the determination of the constants *k* and *p* and the activation energy of the austenite grain growth process for a given steel grade.

As the majority of enterprises dealing with the plastic working of steel do not have a possibility of understanding the initial condition of the material, a decision was made to create a mathematical model based on artificial neural networks for the prediction of austenite grain size prior to hot deformation.

Artificial neural networks are the (software of hardware) simulators of mathematical models, which implement the pseudo-parallel processing of information, and are composed of numerous interconnected neurons and simulate the activity of biological brain structures. The features of neural networks, which are decisive to their great advantages and wide possibilities of application, are [2]:

- parallel processing of information by all links;
- ability of learning and generalizing of data;
- interpolation and prediction;
- considerable resistance to errors (noise) in a set of data;
- ability to operate effectively even partial damage to the network.

The technology of neural networks has been more and more widely applied owing to its capability of easy combination with other problem-solving techniques. In the metallurgy and working of metals, interesting results are obtained by combining the traditional technique with a neural model. There is a possibility of replacing the control programming of a computer or a micro-controller with an easy network-learning process. A key element for the use of neural networks is, however, the fact that they might form a complex, nonlinear model of a phenomenon studied.

2. EXPERIMENTAL

The C15 steel of chemical composition as shown in Table 1 was used for tests. This steel is designed for bulb bars manufactured at the Bankowa Steelworks of Dąbrowa Górnicza.

For the above-mentioned steel grade, tests were carried out with the aim to determine the effect of the method of heating on the size of the primary austenite grain. The tests were

Table 1
The steel of chemical composition

C	Mn	Si	P.	S	Cu	Cr	Ni	Al.
0,14	0.45	0.22	0.018	0.007	0.04	0.03	0.03	0.032
As	N	Mo	Sn	H_2 [ppm]	Nb	V	Ti	Al met
0.003	0.007	0.006	0,003	-	0.001	0.002	0.002	0.028

performed on a DIL 805A/D dilatometer. Cylindrical specimens, each of a length of l=10mm and a diameter of ϕ=4mm, were subjected to different thermal treatment operations. During preliminary laboratory tests, the specimens were hearted up to two different austenitization temperatures of 1050°C and 1180°C, respectively, held at this temperature and then cooled down to the ambient temperature at a rate assuring freezing of the austenitic structure. To determine the effect of soaking time on austenite grain size, different soaking times of t_w=3; 5; 10; 15; 20; 25 and 30 minutes were applied, respectively.

The specimens were subjected to physical-metallurgy examinations. On microsections etched with sodium picrate, the austenite grain size, $d\gamma$, was determined. For this purpose, the secant method was employed, in which the average grain chord, I, is assumed as a linear measure of grain size. The measurement results are given in Table 2.

Table 2
Summary of testing results

Lp.	Heating temperature T[^{0}C]	Time of soaking t_w[s]	Austenite grain size $d\gamma$ [μm]
1	1050	0	48
2	1050	180	70
3	1050	300	72
4	1050	600	85
5	1050	900	94
6	1050	1200	157
7	1050	1500	193
8	1050	1800	265

Lp.	Heating temperature T[^{0}C]	Time of soaking t_w[s]	Austenite grain size $d\gamma$ [μm]
1	1180	0	52
2	1180	180	73
3	1180	300	113
4	1180	600	133
5	1180	900	162
6	1180	1200	185
7	1180	1500	215
8	1180	1800	293

For the simulation of neural networks, the SNNS (Stuttgart Neural Network Simulator) was used. This is a program created by a team of workers at the Institute for Parallel and Distributed High Performance Systems (IPVR) of the Stuttgart University.

For the creation of the neural network, 4 inputs were used, i.e.: carbon gram-equivalent, C_e; initial austenite grain size, $d\gamma_0$; heating temperature, T; and soaking time, t_w. The output in the developed neural network was the austenite grain size, $d\gamma$. For building the neural network, two neurons in a hidden layer were used in one case, and four neurons in a hidden layer in the other. In both cases, the BACKPROPAGATION, or error back-propagation learning function was used, which relies on using the network error as an additional parameter (in the form of corrections) serving for the modification of the values of weights in the program.

3. SIMULATION RESULTS

The developed mathematical model based on artificial neural networks, created by using the SNNS2C program, was written in the form of a dynamic library which was then used in a specially prepared visualization program created using the C language. The consolidated results of experimental studies are shown in Figure 1.

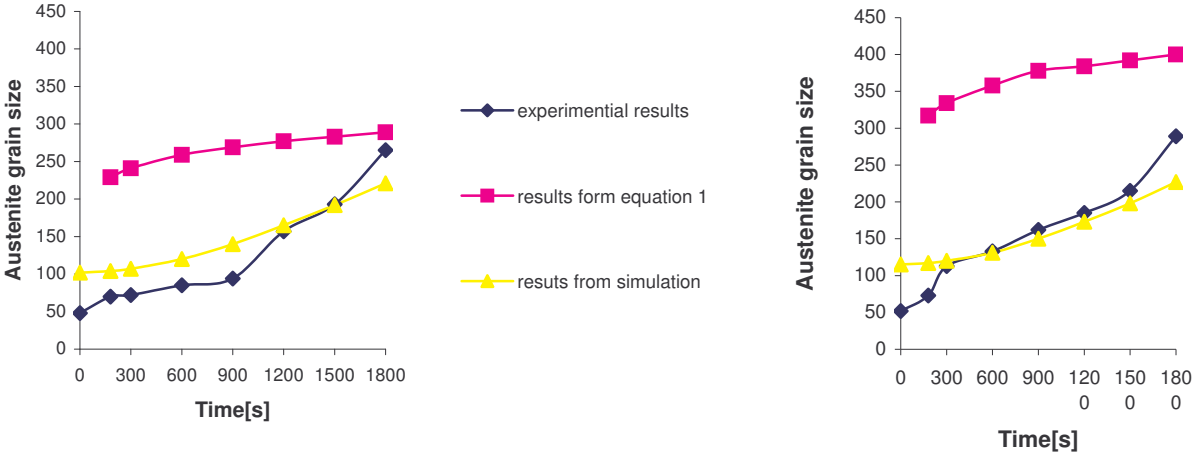

Fig. 1. The effect of soaking time on austenite grain size in isothermal conditions (a-temp. 1050°C b- temp1180°C)

After carrying out the simulation of the prediction of austenite grain size, errors were estimated. Mean percentage errors were about 35%, and mean square errors ranged from 12 to 13%. The greatest differences between the results obtained from experimental studies and those obtained by using the developed program utilizing artificial neural networks occur for the soaking temperature 1050°C in the time intervals from 0 to 900 seconds and from 1500 do 1800 seconds; whereas for the soaking temperature 1180°C, the greatest differences occur in the time intervals from 0 do 300 seconds and from 1500 to 1800 seconds. The mean square error approx. 12%, and the computation time was shortened to a few seconds.

The differences between grain sizes measured and calculated from formula (1) result from the fact that constants given in the literature [5] for steels of a similar chemical compositions were used for calculations. The experimental determination of the energy of grain growth transformation is very complex and requires numerous tests and time-consuming calculations to be carried out.

4. CONCLUSIONS

Attempts were made to develop a mathematical model based on artificial neural networks for the prediction of austenite grain size in the C15 steel. Preliminary results have shown that fast prediction of austenitic structure development is possible. Further studies will be undertaken with the aim to enrich the network learning set with additional records. Increasing their number should improve the accuracy of results and increase the scope of applicability.