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DP steels, continuous annealing,
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COMPUTER SOFTWARE TOOL FOR THE DESIGN OF OPTIMAL THERMAL CYCLES IN THE CONTINUOUS ANNEALING OF DP STEELS

The objective of the paper was development of the software tool, which can be used to design the best continuous annealing technology for DP steels in a fast and efficient way. The model of phase transformations during heating and cooling stages, which is the basis of this tool, is described briefly. Results of identification and validation of the model are presented, as well. Due to complex thermal cycles in the continuous annealing process and large number of the design variables, selection of the optimal technology is difficult. It is expected that the developed model will help to evaluate various technological variants and to compare them. To make this procedure more efficient, the user friendly software was developed. Basic principles and features of this tool are presented in the work. The main functionalities of the software compose simulation of phase transformations during thermal cycles and capability to apply simulations to design the best technological variant. Beyond this a data base, which stores material and technological information for all previously analysed cases, is included in the developed software. Graphical user interface is added to make the software easily accessible and user friendly.

1. INTRODUCTION

Continuous development of the automotive industry creates demand for construction materials that combine high strength with good ductility. Due to their specific microstructure, Dual Phase (DP) steels meet those high requirements and are currently used in the automotive industry [1],[2],[3]. However, introduction of the DP steels into regular production is not fully successful yet and further increase of number of parts made of these steels is still expected (Fig. 1). Manufacturing of DP steels is complex and involves precise control of process parameters. It is expected that numerical simulation of manufacturing chain will help to design the optimal process. Thus, development of the model, which is capable to simulate phenomena occurring in the DP steels, is important. Model of phase transformations during heating and cooling stages of the continuous annealing process was

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developed by the Authors and is described in the paper. The model was identified on the basis of dilatometric tests and validated by comparison with the results of physical simulations [6]. The model can evaluate various technological variants (complex thermal cycles) and easily compare them. On the other hand, large number of the design variables does not allow efficient simulation of all the thermal cycle variants and selection of the best one. Therefore, development of the user friendly software tool based on the mentioned model was the main objective of the present work.

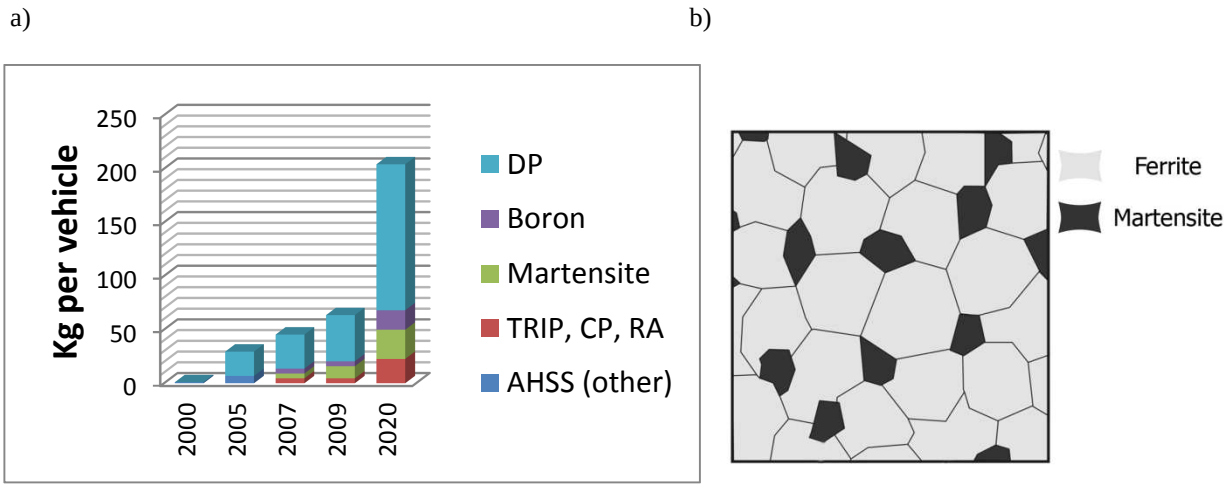

Fig. 1. Prediction of development of parts made of DP steels in car body (a) and schematic illustration of the two-phase microstructure (b)

2. DUAL PHASE STEELS

The DP steel is a composite of ductile ferrite and hard martensite phases. Volume fraction of martensite or MA (martensite with small islands of the retained austenite) cannot exceed 30%, usually it is between 15 and 25%. This phase composition gives high strength and good workability. Main advantageous features of the DP steels are lack of the upper/lower yield points, low $R_{0.2}/R_m$ ratio and high hardening coefficient. As a result, these steels reach relatively large uniform and total elongation in the tensile tests. Schematic illustration of the two-phase microstructure is shown in Figure 1b. Soft phase (ferrite) maintains its continuity what gives good ductility. Deformation of this structure gives advantageous characteristic of hardening comparing to typical HSLA steels. Capability to accommodate the energy of deformation during accidents is an important advantage from automotive industry point of view. The DP steels technology requires application of dedicated cooling paths to obtain pure ferrite-martensite microstructure or ferrite-martensite/bainite one. The capability of modelling phase transformations is essential to define the cooling conditions for the technology design for these steels. The identification of such a model through the inverse analysis of the dilatometric tests is the subject of following chapters. See [4],[5] for more information on DP steels.

3. MODELS

The model should allow realistic description of the process, good accuracy and reliability of calculations, as well as should provide special predictive capabilities. Model of phase transformations during heating and cooling was developed and is described in [6]. Main equations of the model are repeated below. The transient model is based on Avrami equation [7]:

$$X = 1 - \exp\left(-kt^n\right) \tag{1}$$

where: X – volume fraction of the new phase, t – time.

Equation (1) is combined with the Scheil additivity rule [8], which accounts for the temperature variations. Theoretical considerations show that a constant value of n in equation (1) can be used for modelling ferritic, pearlitic and bainitic transformations (n_f, n_p, and n_b respectively). On contrary, value of the coefficient k must vary with temperature T. The formalism of the function $k = f(T)$ must be carefully chosen to describe properly the transformation kinetics. A modified Gaussian function proposed in [9] was selected for the ferritic transformation:

$$k_f = k_m \exp\left[-\left(\frac{T - T_n}{p}\right)^q\right] \tag{2}$$

The coefficients k_m, T_n, p and q allow description of all shapes of the CCT diagram in an intuitive way. Thus, $k_m = a_1/D_\gamma$ is the maximum value of k, $T_n = \mathrm{A_{e3}} + 400/D_\gamma - a_2$ is a position of the nose of the modified Gaussian function (2), p determines the nose width at mid height of this function and q controls the sharpness of the curve. D_γ is the austenite grain size prior to transformation. The sensitivity analysis performed in [10] has shown that the output of the model is not sensitive to coefficients describing relation $k = f(T)$ for the pearlitic transformation. Therefore, the model for this transformation was simplified and constant value of $k = k_p$ was assumed. The following equation describes k for the bainitic transformation:

$$k_b = b_6 \exp\left(b_5 - 0.01 b_4 T\right) \tag{3}$$

For lean chemical composition of a steel the Avrami equation (1) with the modified Gauss function (2) describes properly nucleation, growth and site saturation mechanisms. Thus, it accounts directly for the incubation time for the ferritic transformation. An assumption is made that this transformation begins when 5% of ferrite is predicted in the microstructure. Incubation time has to be introduced for pearlitic (τ_p) and bainitic (τ_b) transformations:

$$\tau_P = \frac{p_1}{\left(\mathrm{A}_{e1} - T\right)^{p_3}} \exp\left[\frac{p_2}{R\left(T + 273\right)}\right] \qquad \tau_b = \frac{b_1}{\left(B_s - T\right)^{b_3}} \exp\left[\frac{b_2}{R\left(T + 273\right)}\right] \tag{4}$$

where: R – gas constant, B_s – bainite start temperature:

$$B_s[^{\circ}\mathrm{C}] = b_0 - 425[\mathrm{C}] - 42.5[\mathrm{Mn}] - 31.5[\mathrm{Ni}] \tag{5}$$

Start temperature for the bainitic martensitic transformations (M_s) is given by:

$$M_s[^{\circ}\mathrm{C}] = m_1 - m_2 C_\gamma \tag{6}$$

where: C_γ – current carbon content in the austenite.

Fraction of austenite, which transforms into martensite, is calculated as [10]:

$$X_m = 1 - \exp\left[-0.011\left(M_s - T\right)\right] \tag{7}$$

where: X_m – the volume fraction of martensite with respect to the whole volume of austenite, which remains at M_s. This fraction with respect to the whole volume of the sample is:

$$F_m = \left(1 - F_f - F_p - F_b\right)\left\{1 - \exp\left[-0.011\left(M_s - T\right)\right]\right\} \tag{8}$$

where: F_f, F_p, F_b – volume fractions of ferrite, pearlite and bainite, respectively.

Two processes occur during the heating stage, recrystallization of ferrite and phase transformation of the ferritic-pearlitic microstructure into austenite. In the range of heating rates used in the industry the former has small influence on the structural composition of products and is not considered in the paper. Model of the phase transformation during heating is also based on equation (1) with the coefficient $n = n_h$ and coefficient k defined as:

$$k_h = h_4 \exp\left[\frac{h_5}{R\left(T + 273\right)}\right] \tag{9}$$

Incubation time for the ferrite-austenite transformation is calculated from the equation:

$$\tau_h = \frac{h_1}{(T - A_{e1})^{h_3}} \exp\left[\frac{h_2}{R(T + 273)}\right] \tag{10}$$

Coefficients in equations (1)-(10) for the DP600 steel containing 0.08%C, 1.74%Mn, 0.12%Si, 0.23%Cr, 0.009%P, 0.01%S and 0.001%N were identified on the basis of dilatometric tests and inverse algorithm described in [6]. Obtained values of these coefficients are given in Table 1. The model with identified coefficients was used to simulate the continuous annealing in the present work.

Table 1. Coefficients in the model determined from the dilatometric tests

n_h	h_1	h_2	h_3	h_4	h_5	n_f	a_1	a_2	p	q	n_p	p_1
1.245	130.5	1.265	2.743	196.1	2.9×10^8	1.4	7.0	211.1	41.4	1.52	0.74	1395
p_2	p_3	k_p	n_b	b_0	b_1	b_2	b_3	b_4	b_5	b_6	m_1	m_2
66.4	3.5	0.122	0.556	690.3	25.1	24.9	1.79	0.006	0.282	0.495	414	3.07

4. CONTINUOUS ANNEALING

The continuous annealing in the intercritical region is a part of manufacturing chain for DP steels, which is now commonly used to obtain dual phase microstructure composed of soft ferrite and hard martensite. In this process certain amount of ferrite remains in the microstructure after heating and carbon distribution in the austenite is nonuniform. The microstructure of the steel at the beginning of the annealing process usually is a deformed ferrite/pearlite mixture. A typical thermal cycle of the continuous annealing in the intercritical region is shown in Figure 2a. The process begins with heating with the rate of about 3^{o}C/s. The static recrystallization of ferrite occurs first. When temperature exceeds A_{c1} transformation of ferritic-pearlitic microstructure into austenite begins. In the intercritical region the isothermal holding or very slow heating with the rate of about 0.25^{o}C/s is applied, generally not longer than 40-60s. A two-phase microstructure of ferrite and austenite is obtained. Cooling process begins next and it is usually composed of fast/slow and fast cooling rate periods. After the first two periods part of the austenite transforms back to ferrite. In the last period of quenching any remaining austenite is expected to transform to martensite, resulting in the characteristic ferrite/martensite dual phase steel microstructure. Typical example of such microstructure obtained from SEM is shown in Fig. 2b.

a) b)

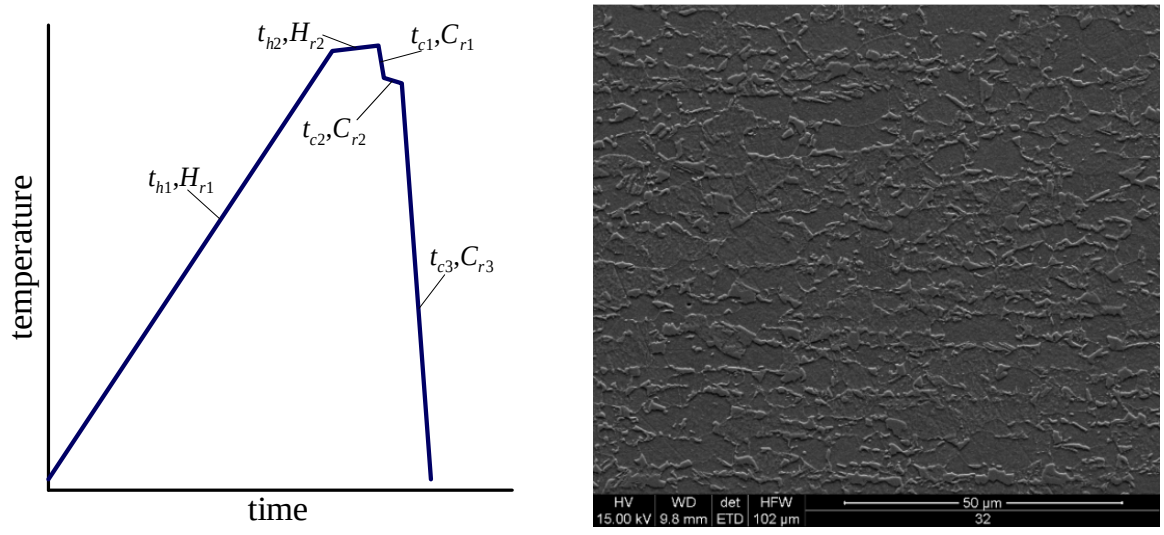

Fig. 2. Schematic illustration of the thermal cycle for the intercritical continuous annealing (a) and typical SEM microstructures obtained after continuous annealing (courtesy of R. Kuziak from IMŻ Gliwice) (b)

Presented model was incorporated into the developed user friendly software, that can be used for practical technology design.

5. SOFTWARE TOOL

As mentioned, the main functionalities of the tool compose simulation of phase transformations during thermal cycles and application of the optimization techniques to design the best technological variant. Beyond this a data base, which stores material and technological data for all previously analysed cases, was included in the software. Finally, a user friendly interface is added to make the software easily accessible and efficient.

Thus, proposed tool consists of a set of modules, which perform various functions:

- GUI (Graphical User Interface) layer, which allows to use application in an intuitive manner, controls correctness of the introduced data and presents obtained results.
- Database implemented with SQLite library is used to store steels and projects data in an efficient way.
- Console-based solver performs all the simulation.
- Plotting and plot exporting library are used for visualization purposes.

The software is a lightweight and portable application, performing basic actions such as:

- creation and storage of steel parameters,
- creation, storage and management of projects (Figure 3),
- simulation of continuous annealing processes in verification mode before permanent parameters change and in recalculation mode to update results in the data base,
- visualisation of results and comparing them with results from other projects,
- export of stored results in the form of diagrams and text files,
- quick preview of project parameters before loading selected one from the list of projects.

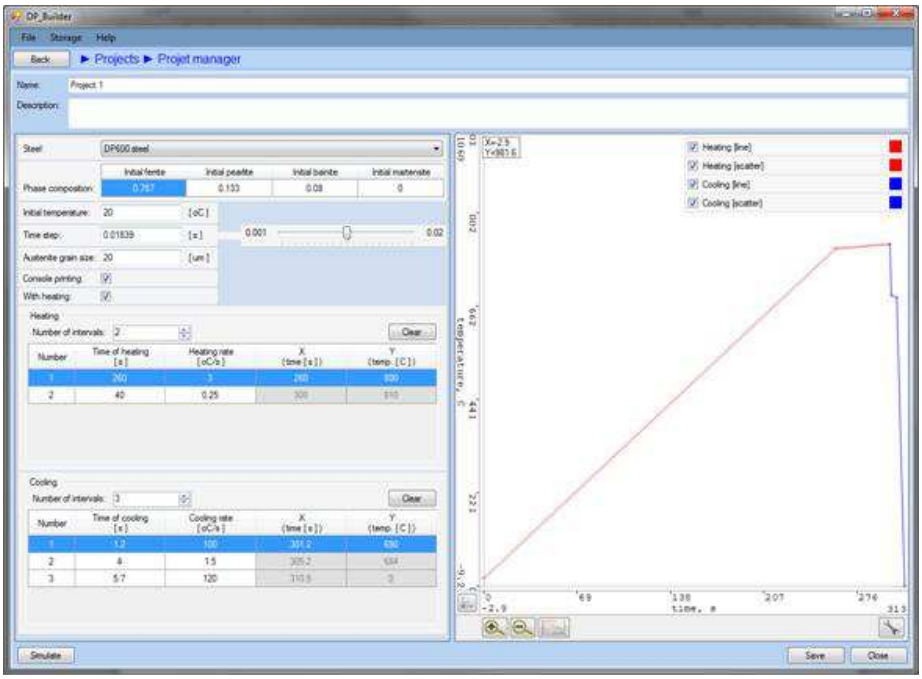

Fig. 3. Project manager mode of the DP_Builder software

In the designed project, the user can control following parameters:

- phase composition, which includes initial content of ferrite, pearlite, bainite and martensite in the microstructure after cold rolling,
- initial temperature of the process,
- time step of the simulation,
- selection of thermal cycles for heating and cooling phases.

6. RESULTS

Steel with the chemical composition given in Chapter 3 was investigated. Selected results of simulations of the continuous annealing performed using the developed software are presented below. Three thermal cycles were designated to demonstrate the capabilities of the tool. Parameters of investigated thermal cycles are given in Table 2. Starting temperature for each cycle was 20^{o}C and the microstructure contained 79% of ferrite, 13% of pearlite and 8% of martensite. The austenite grain size after heating stage was 20μm. It is shown in [11] that slight changes of the parameters in Projects 1, 2 and 3 result in different carbon distributions, while volume fractions of ferrite and martensite remain similar. This result was confirmed by the simulations using the developed software.

Table 2. Parameters of investigated projects

<table>
<tr><th colspan="2"></th><th>Project 1</th><th>Project 2</th><th>Project 3</th></tr>
<tr><td rowspan="4">Initial phase composition (sum equal 1)</td><td>Ferrite</td><td>0.787</td><td>0.787</td><td>0.787</td></tr>
<tr><td>Pearlite</td><td>0.133</td><td>0.133</td><td>0.133</td></tr>
<tr><td>Bainite</td><td>0.08</td><td>0.08</td><td>0.08</td></tr>
<tr><td>Martensite</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td colspan="2">Initial temperature [^{o}C]</td><td colspan="3">20</td></tr>
<tr><td colspan="2">Time step [s]</td><td colspan="3">0.01839</td></tr>
<tr><td colspan="2">Heating (2) and Cooling (3) intervals</td><td>
<table>
<tr><th>Time [s]</th><th>Rate [^{o}C/s]</th></tr>
<tr><td>260</td><td>3</td></tr>
<tr><td>40</td><td>0.25</td></tr>
<tr><td>1.2</td><td>100</td></tr>
<tr><td>4.0</td><td>1.5</td></tr>
<tr><td>5.7</td><td>120</td></tr>
</table>
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<table>
<tr><th>Time [s]</th><th>Rate [^{o}C/s]</th></tr>
<tr><td>265</td><td>3</td></tr>
<tr><td>40</td><td>0.25</td></tr>
<tr><td>1.2</td><td>100</td></tr>
<tr><td>12.5</td><td>1.5</td></tr>
<tr><td>5.72</td><td>120</td></tr>
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<tr><th>Time [s]</th><th>Rate [^{o}C/s]</th></tr>
<tr><td>265</td><td>3</td></tr>
<tr><td>40</td><td>0.25</td></tr>
<tr><td>1.0</td><td>100</td></tr>
<tr><td>19.5</td><td>1.5</td></tr>
<tr><td>5.79</td><td>120</td></tr>
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Typical screens with selected results of simulations are shown in Figs. 4, 5 and 6. Comparison of changes of the ferrite volume fraction for the three investigated projects is presented in Fig. 4. Current values of this volume fraction during annealing are different.

Project 1 represent inter critical annealing, in which transformation of the ferritic-pearlitic microstructure into austenite was not completed. Full austenitization was obtained for projects 2 and 3. However, in spite of these differences the final volume fraction of the ferrite are similar.

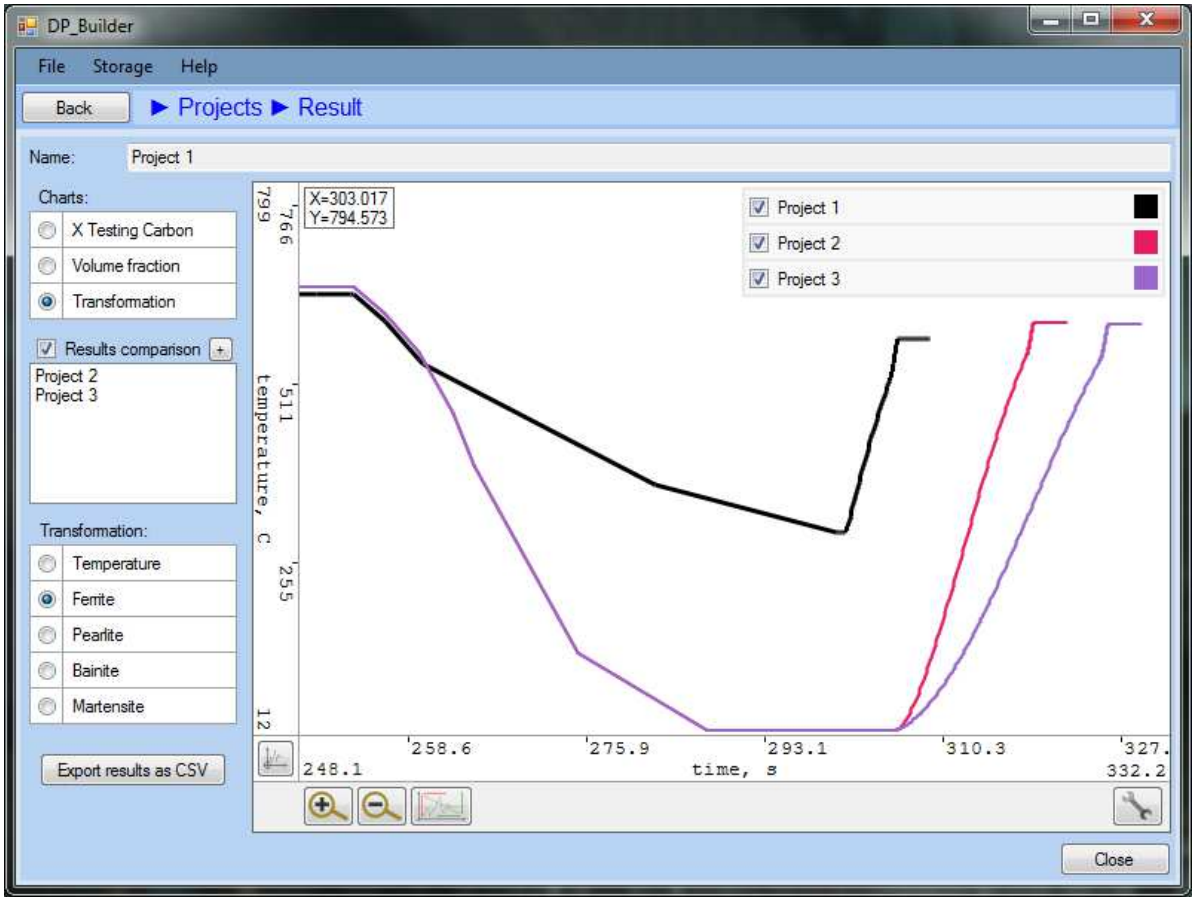

Fig. 4. Comparison of changes of ferrite volume fractions for different projects for the DP600 steel

Typical plot of changes of the average carbon concentration in the austenite are shown in Fig. 5. During heating carbon concentration is close to the equilibrium and after heating it reaches concentration in the steel (0.08%C). During the first stage of fast cooling the progress of the ferritic transformation is negligible and carbon concentration almost does not change while the temperature drops. In the second stage (slow cooling) fast progress of the ferritic transformation is observed and carbon concentration increases while the temperature drops only slightly. In the third stage (fast cooling) progress of the ferritic transformation is slow and carbon concentration increases slightly while the temperature drops rapidly. Changes of the carbon concentration calculated for the three investigated project are shown in Fig. 6. It is seen in this figure that current values of the concentration during annealing are different but the final values are similar. These values are determined by the final volume fraction of the ferrite.

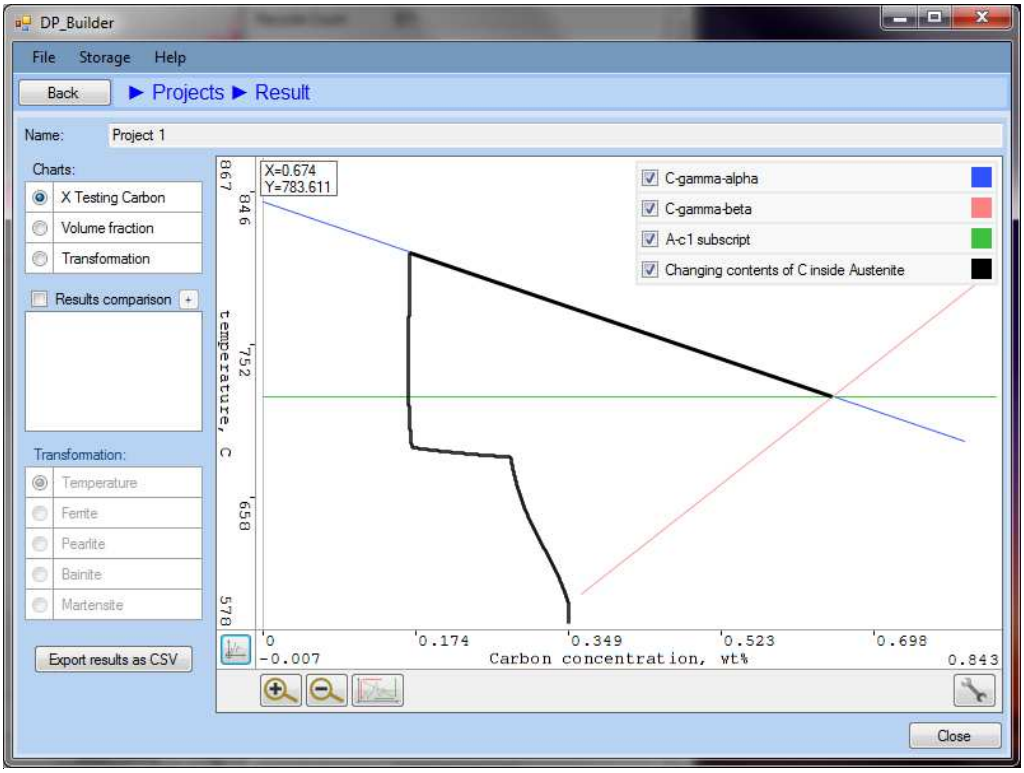

Fig. 5. The average carbon concentration changes in the austenite for the DP600 steel

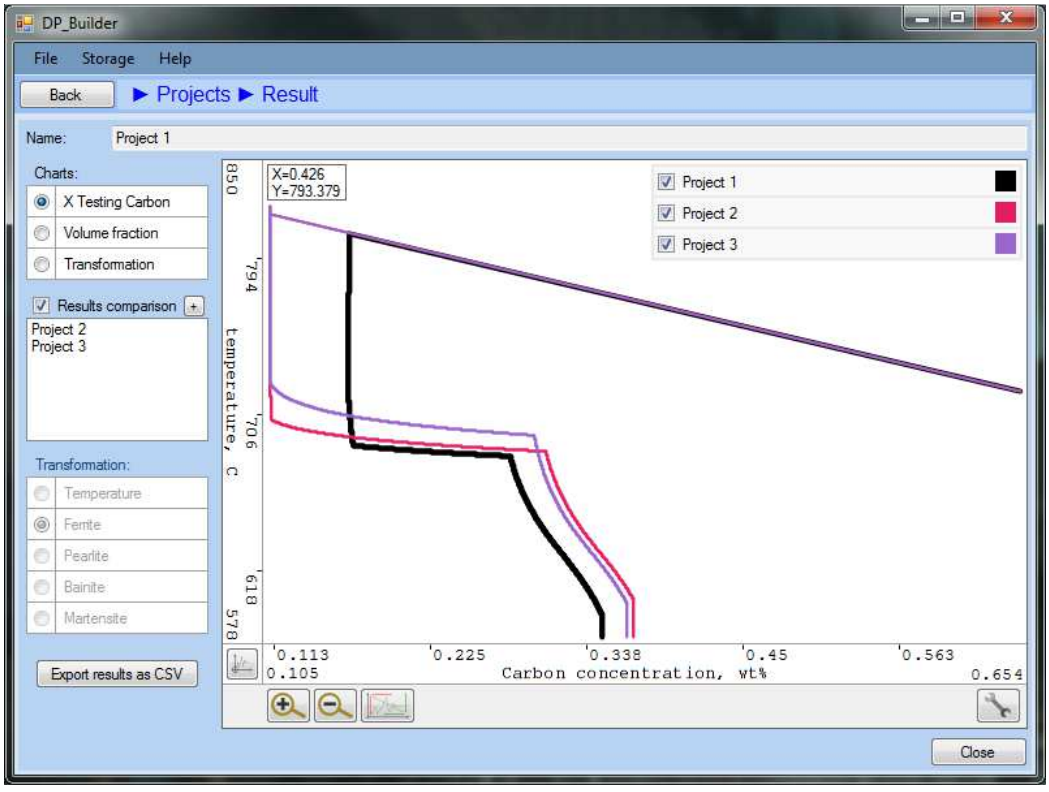

Fig. 6. Comparison of results of carbon concentration changes obtained from different simulations for the DP600 steel

7. CONCLUSIONS

The software, which allows to design the continuous annealing technology for the DP steels was presented in the paper. The virtual model of the industrial annealing process is the main part of the tool. Beyond this, the following designed functionalities of the should be pointed out:

- possibility to store data,
- user-friendly interface,
- convenient visualization of data,
- capability to simulate phase transformation during complex thermal cycles.

The developed software can support the design of the best thermal cycle, which should be applied in the continuous annealing line to obtain the required phase composition of the DP steel.

ACKNOWLEDGEMENTS

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