Determining the optimum heating time of small sized test specimen made from weldable mild steel

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Abstract. The usage of CHT (Continuous Heating Transformations) diagrams for a given steel or equivalent grade, requires knowledge of heating temperature, average heating rate, and the heating time. Definition of these technological parameters are primarily based on the complex relationship system between the geometric, thermal parameters and the heating device. In our research, we mainly focused on those physical key parameters that can mostly influence the heating and transformation rate. These parameters provide realistic, usable data for analysing the process of thermal diffusion and FEA (Finite Element Analysis) tests. During analysis, an easy-to-use function relationship was determined for approaching the heating rate more precisely. This method allows handling the CHT charts easily, within a selected range, regarding weldable mild steels.

1. Introduction
A steel component of the selected material grade have to be austenitized with a certain average heating rate for heat treatment. The heating rate gives the relationship of the geometry and the heating furnace between the heating temperature and the time required for heating. However, the relationship appears only indirectly on CHT charts for a given material quality. Therefore, the average heating rate is an important technological parameter, its simple definition is important for engineers. In this point of view, the data for heating technology are just relatively well-defined for specific industrial processes and special laboratory procedures [1]. The goal of our research was to work out an easy-to-use and properly accurate approximation method for typical 20 mm of diameter specimens made from weldable mild steels that has an acceptable estimate result for heating rate or the heating time.

2. Applied method and modelling for the task
Our work was fundamentally based on the Reverse Engineering Techniques (RET). Based on practical measurement results and data, we have interpreted the heat transfer processes necessary to use the CHT diagrams and to achieve our goal. During the heating experiments, we used an electric resistance-heated furnace type K-28/1100 with a power of 3.5 kW and a PID (Proportional Integral Derivative) control system, without usage of ventilator.

The specimens were cut out of the columnar crystallized zone of a 100x100 mm billet that originated from continuous casting, in this way ensuring a homogeneous material structure. The material structure was also improved by the rolling ratio (RR is 6) of billet. The grain structure of the specimens consisted of ferrite and perlite, corresponds to the grain size class of ASTM 10-11. The carbon equivalent value (CE according to spec. EN 1011-2/A) is 0.483, so this material grade has a good weldability.
The most important data of the experimental S460N material grade used for the heating experiments compared to standard S460N material grade can be seen in Table 1.

| Composition (wt%) | C  | Mn  | Ni  | Si  | Al  | Cu  | Ti  | V   |
|------------------|----|-----|-----|-----|-----|-----|-----|-----|
| experimental S460N | 0.141 | 1.5 | 0.62 | 0.18 | 0.008 | 0.2 | 0.0067 | 0.186 |
| standard S460N | max. | 0.2 | 1.0-1.7 | max. | 0.6 | max. | max. | max. |

The geometry of the test specimens is characterized by Ø20x60 mm. Along the centreline of the specimens a cylindrical borehole with a diameter of Ø3 mm and 30 mm deepness was made for the thermocouple. The installation and adjustment of the thermocouple required very careful preparation and several tests [2]. The heating temperature of the specimens were set at 1050 ºC and we strove to achieve the fine-grained austenitic microstructure.

The specimens were individually heated to determine the minimum heating time and maximum heating rate. We wanted to characterize the relationship between the thermal conductivity of the small-cross sectioned specimen and the surface heat transfer using the Biot number (1):

$$B_i = \frac{\alpha_{EHTC}}{\kappa_E} \cdot L$$  \hspace{1cm} (1)

whereabout:

- $B_i$ the Biot number is a dimensionless quantity (-)
- $\alpha_{EHTC}$ the effective heat transfer coefficient (sum up convection and radiation) (W/m²·K)
- $\kappa_E$ the effective thermal conductivity of scaled specimen (W/m·K)
- $L$ the characteristic length (ratio of the volume and the cylindrical surface) (m)

The Biot number is a simple index of the ratio of the heat transfer resistances inside and on the surface of specimen. If this index is smaller than 0.1, the heat flux is determined by the heat transfer ability on the surface. For determination of Biot number, we needed data of time and temperature inside the specimen. Therefore, several heating experiments were performed. A typical result of the experiments is shown in Figure 1.

![Figure 1](image-url)
As shown in Figure 1 we drew a good approximated function onto the heating curve recorded by measurement. The measurement graph contains some measurement noise, which is unnecessary to consider [3]. This solution allowed us to handle thousands of data in the future in a simple way.

In the following step, we determined the effective heat transfer coefficient acting on the surface of the specimen. This factor is the cumulative value of the convective and radiative heat transfer [3,4] (2).

\[ \alpha_{EHTC} = \alpha_C + \alpha_R \] (2)

whereabout:
- \( \alpha_C \) the convective heat transfer coefficient (W/m²K)
- \( \alpha_R \) the radiation heat transfer coefficient (W/m²K)

In the preheated electric resistance-heating furnace, the heat transfer is basically determined by the thermal radiation. This effect increases with increasing the surface temperature of the specimen (3).

\[ \alpha_R = \frac{\sigma \cdot \varepsilon \cdot (T_F^4 - T_S^4)}{T_F - T_S} \] (3)

whereabout:
- \( \sigma \) the Stefan–Boltzmann constant (5.67×10⁻⁸ W/m²K⁴)
- \( \varepsilon \) dimensionless emissivity constant. (its value is 0.8 because of ceramic walling of furnace) (-)
- \( T_F \) the air temperature in the furnace (K)
- \( T_S \) the surface temperature of the specimen (K)

It should consider that in the absence of a ventilator, the airflow near the surface might be a natural convection. In this case, with consideration of all efficiency, for determining convectional heat transfer coefficient, the following mathematical expression could be used which derived from the discontinuous furnace performance:

\[ \dot{Q} = \frac{c_p \cdot \dot{m} \cdot (T_S - T_0) \cdot 3.6}{t \cdot 1000 \cdot \eta} \rightarrow q = \frac{\dot{Q}}{A_S} \rightarrow \alpha_C = \frac{q}{T_F - T_S} \] (4)

whereabout:
- \( \dot{Q} \) the amount of heat flux per unit time (J/s or W)
- \( q \) the amount of heat flux per unit time and unit surface (W/m²)
- \( T_0 \) the initial temperature of surface (298 K or 25 °C)
- \( t \) the heating time of specimen (measured) (sec)
- \( c_p \) the amount of specific heat on constant pressure (600 J/kg·K or 600 J/kg·°C)
- \( \dot{m} \) the performance per hourly of furnace on the actual temperature (kg/h)
- \( A_S \) the surface of the specimen (m²)
- \( \eta \) the technological efficiency of the furnace (80%)

The results of the calculations are summarized in Figure 2. The figure shows two graphs. The upper graph is the sum of heat transfer coefficients, the lower is the heat convection coefficient, as a function of temperature. At a temperature of 500 and 600 Celsius, the heat transfer coefficient was determined by the adjusted polynomial that is visible on Figure 1. From the diagrams, we can conclude that the effective heat transfer coefficient grows parabolically, depending on the heat radiation. The value of the heat convection coefficient decreases below 10 in the range of 300-800 Celsius. The change in this interval is small and its minimum value falls in the range of 500-600 Celsius, which can be related to
the powerful scale formation. However, convection heat transfer is not significant. The average of the heat convection coefficient corresponds to the values normally used for natural airflow [4].

\[
y = 0.0003x^2 + 0.0013x + 181.73
\]

\[R^2 = 0.9991\]

\[\alpha_{\text{C}} = 293 \text{ (W/m}^2\text{°C)}\]
\[\alpha_{\text{e}} = 16.5 \text{ (W/m}^2\text{°C)}\]
\[\alpha_{\text{R}} = 276.5 \text{ (W/m}^2\text{°C)}\]

**Figure 2.** Graph of the effective and the convective heat transfer coefficients as a function of temperature

For structural steels, the thermal conductivity varies linear from room temperature to 800 °C, the thermal conductivity reduces from 55 W/m·°C to 28 W/m·°C. From this point, the thermal conductivity does not change with further temperature increase [4, 5, 6]. During examination, the smallest value of thermal conductivity was considered. For this reason, the average thickness of the scale was considered in this range. Consequently, we had to measure the thickness of the formed scale on the surface after heated to 1050 °C. We considered the thermal conductivity of the scale to be 2.5 W/m·°C, based on the above and related literature references [6, 7]. Based on the law of J. Païdassi the following relationship for pure iron to determine the layer thickness of the scale [8]:

\[
x = 24550 \cdot \exp\left(-\frac{84650}{RT}\right) \cdot \sqrt{t}
\]

whereabout:
- \(x\) the scale magnitude at an instant (μm)
- \(R\) the universal gas constant (8.314 J/K·mol)
- \(T\) the heating temperature (K)
- \(t\) the heating time of specimen (measured) (sec)

After cooling of specimen, the scale thickness was measured by HITACHI SN3400 Scanning Electron Microscope. Based on our measurements the relationship (5) was corrected by a simple coefficient. The coefficient takes into account the tendency of manganese alloy mild carbon steels to scaling at a high temperature (6).

\[
x = 24550 \cdot \exp\left(-\frac{84650}{RT}\right) \cdot \sqrt{2t}
\]

The scale thickness were determined based on the Equation (6). The average scale thickness of the samples heated to 1050 Celsius was calculated of 97.815 microns. This value approximates the average of the measurement results well, which can be seen on Figure 4. The thickness of the scale relative to the cross-section of the specimen is negligible, however, due to its inferior thermal conductivity, we did not ignore it. Therefore, the specimen thermal conductivity was modified to 27.75 W/m·°C.
Taking into account the experimental results and calculations, the value of Biot number is 0.05. It can be stated that the value obtained is lower than the threshold value. This means that the heat transfer time only depends on the process of heat transfer on the surface, the heat flux distribution is uniform in the cross-section of material. The test results mentioned above were checked by a finite element method. For finite element studies, we used the Simufact.forming version of 15.0.

The key pre-processing data:
- 3D-FE solver usage, mesh generation by tetrahedron (134), element size is 1.235 mm
- the effective heat transfer coefficient on the surface is 293 W/m² K
- material grade from softer database, DB_S460M_h
- the heating temperature is 1050 °C
- the heating time is 493.4 sec
- the emission coefficient of steel on temperature of 25 °C is 0.25.

The key post-processing data:
- the exit number of analysis is 3004
- based on the pre-processing data the maximum heating temperature is 1049.85 Celsius.

The difference is only 0.15 °C from 1050 °C. This difference is actually negligible. The result of the analysis can be seen in Figure 4. It confirms that the temperature distribution is uniform over the entire cross section of the workpiece based on the experimentally determined data.
3. Examination of heating rate and material structure

In order to produce linear heating rate curves, the temperature-time relationships had to be linearized. For this, we first needed a straight line to fit onto the endpoints of the heating curve. Based on the heating curve in Figure 2, the average heating rate was determined at 2.077 °C/sec, practically rounded to 2.1 °C/sec. Then a simple algorithm was used to determine the temperature-time relationships derived from the furnace power data using this constant heating rate. Certainly, there are simpler mathematical solutions as well, but the furnace technology data cannot be separated from recording the heating curves. Equation (7) gives the linearized time data by furnace power set at a constant heating rate of 2.1 °C/sec.

\[
t = \frac{m \cdot 3600}{m \cdot \eta} \cdot k_E
\]

whereabout:

- \( t \) the heating time of specimen (calculated) (sec)
- \( m \) the mass of the specimen (kg)
- \( \dot{m} \) the furnace power per hour (kg/h)
- \( \eta \) the technological efficiency of the furnace (80%)
- \( k_E \) the dimensionless cumulative correction factor that takes the additive effects of geometry, shape and furnace type into account (-)

Based on the results, a simple and good approximation function relation can be obtained from the linear equation. The function relation can also provide a good approximation of temperature-time relationship referring to heating rate (8).

\[
a) t (\text{min}) = \frac{T [\degree C]}{127} \quad b) t = \frac{\frac{v_{(2)}}{v_{(1)}}}{\frac{v_{(2)}}{v_{(1)}}}
\]

whereabout:

\( \frac{v_{(2)}}{v_{(1)}} \) the heating rates ratio in the same dimension (e.g. 2.1(°C/sec) / 3(°C/sec) = 0.7).

The simplified function of formula (8a) (red circle, details below) in Figure 5 fit well to the values calculated from formula (7) (black triangle, details above).

![Figure 5. The constant heating rate as a function of temperature - time](image-url)
Using the equation (7) and the very precise approximation shown in Figure 5, the heating rate functions can be generated in the usual form. In the case of relation (8b), the heating rates, shown in parentheses, we mentioned only as examples. Using this formula the function can be generated at any arbitrary heating rate. It is easy to see, if that heating rate is closer to the determined heating rate, we can obtain results that are more accurate. By plotting the time data of the relationship on a logarithmic scale, we can obtain the well-known heating rate function, which is applicable on the CHT diagram.

The examined structural steel S460 can be considered Mn alloy carbon steel as well. This explains that the scale was stronger than expected, actually can also be detected in the austenitic grade.

The specimens were heated to 1050 degrees Celsius for eight minutes and approximately fourteen seconds for material structure studies. After reaching the specified temperature and time, the specimens were quenched in water at 20 degrees Celsius. As a quenching result, the obtained martensitic structure showed the original austenitic crystal boundaries, which were examined according to ASTM E112-13 (Heyn Lineal Intercept Procedure, magnification = 50x).

As a result of the examination, we found that the grain size satisfied grade 5-6, closer to grade six. The typical average grain size in the middle of the samples is 51.6 microns. The typical average grain size near the surface cross-sections of the samples 57.3 microns. Observably, the material needs more Ti or Nb alloys for finer grain structure at high temperature [9, 10].

As a result of the microstructural analysis, we found that the material structure does not contain coarsened grain, locally duplex structure. The composition of the material is characterized by a homogeneous, average grain size. It follows that the method presented for determining the heating rate is admissible.

4. Summary, conclusions
In this article, we reported on the partial results of a research process. In our work, we have dealt with a possible method of generating the technological data needed to heat the C-Mn steels with a cross section typical 20 mm of diameter. Based on the experience of the experiment, we drew conclusions that can be found in the relevant chapters.

The results, which are considered important, are summarized as follows:

- the effective heat transfer coefficient grows parabolically, basically depending on the heat radiation
- the scale thickness were well approachable on the Equation (6), although the thickness of the scale relative to the cross-section of the specimen is negligible
- the finite element analysis confirmed that the temperature distribution is uniform over the entire cross section of the workpiece based on the experimentally determined temperature-time data, so the applied method is satisfactorily precise
- the simplified functions of formula (8a) and 8(b) are a satisfactorily precise approximation to the determined heating rate function, so converted to logarithmic scale are applicable on the CHT diagram as well
- the microstructural analysis has confirmed, the heated material of S460 has a homogeneous and average grain sized structure, so the method presented for determining the heating rate is usable

Overall, we can say that our subtask goal was mostly met, and we managed to define a simple method for easier handling of CHT curves.

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