Journal of Applied
Technical and Educational Sciences
jATES

ISSN 2560-5429

http://jates.org

jATES
Journal of Applied
Technical and
Educational Sciences

A practical based determination of preheating temperature of high strength steels welding

Lama Mkanna [1*,2]

[1*] Ph. D student, Szechenyi Istvan University, Gyor 9026, Hungary, Lamamkanna@gmail.com

[2] Teacher assistant, University of Dunaujvaros, Dunaujvaros 2400, Hungary, mkannalama@uniduna.hu

Abstract: *This study introduces a straightforward method for calculating preheating temperature in steel welding, combining hardness testing with graphical representations of cooling time. The approach begins with hardness tests on welded joints, providing essential insights into material behavior under different cooling conditions. Graphical diagrams are then created to illustrate the relationship between hardness values and cooling times. These diagrams facilitate the selection of optimal cooling times for desired hardness levels. By integrating these diagrams with an existing C++ program, preheating temperature can be easily determined based on the chosen cooling time. This streamlined approach enhances the accuracy of preheating temperature calculations, ultimately improving weld quality and structural integrity.*

Keywords: *Preheating temperature, Hardness testing, Steel welding, Cooling time analysis, Graphical representations, Simplified methodology.*

1. Introduction

This paper discusses the possibility of having a serious defect in the welding which is the Cold cracking, or hydrogen-induced cracking, generally occurs at temperatures below 200℃. It is also called “delayed cracking” due to the incubation time required for crack development. It is generally accepted that cold cracking will occur when the following factors are present simultaneously: diffusible hydrogen in the weld metal, a susceptible microstructure, and residual stress. In the past, cold cracking was most commonly observed in the heat affected zone (HAZ) of high-strength steels, and for avoiding the cold cracking, some have proposed the use of a carbon equivalent as a steel weldability indicator, with the principal aim being the determination of the minimum necessary preheating temperature for welding high-strength structural steels, because the most reliable and fail-safe measure to avoid cold cracking is preheating, it is able to allow a low cooling rate to obtain a lower hardness value for the HAZ. The known principal factors influencing cold cracking in weld metal are the strength of the weld metal, hydrogen level, microstructure, restraint, and weld cooling rate. (Kou, 1987), (Yurioka, 2001), (Yurioka & Kasuya, 1995) (Sun & Dilger 2023) (Kvackaj et al 2021).

The aim from this paper is to give new findings regarding calculating the preheating temperature by using a simple C++ program that takes in a map representing the chemical composition of the steel (carbon and manganese content), as well as the thickness and welding speed as parameters. The program then calculates the preheating temperature using predetermined coefficients and returns the result, (Dale & Weems 2004) (Hubbard, 2021), (Abdulkareem & Abboud, 2021).

Additionally, the paper presents new graphs according to my results during testing the hardness after the Gleeble 3500 simulation, I included thermo-mechanically treated steels in the thermal process modeling, namely S355MC, S500MC, S700MC, S960MC, and S1100MC. The cooling time was set to 5 seconds, 10 seconds, 15 seconds, and 20 seconds within the temperature range of 800°C to 500°C.

The created graphs present the relation between the hardness values and the cooling time, which will be helpful to determine the preheating temperature as well.

2. Determining the critical cooling time

According to welding heat input theories, which describe the heat process occurring at different points of the welded joint, for example, Rosenthal and Rykallin theories (Yurioka, 2001), the heat cycle typically formed at a specific point can be described. The heat cycle based on physical principles is shown in Figure 1.

The notations used in the figure are as follows:

- [T] temperature,
- [t] time,
- [Tmax] maximum temperature,
- [Tcrit] critical temperature,
- [W(T)] cooling rate measured at a given temperature (T),
- [Th] overheating time, the time spent above the Tcrit temperature,
- [T1] upper temperature at which the cooling time is measured (in our case, 850°C),
- [T2] lower temperature until which the cooling time is measured (in our case, 500°C),
- [Δt8/5] cooling time between 850 and 500 °C, critical cooling time,
- [ΔtT1-T2] cooling time between temperatures T1 and T2.

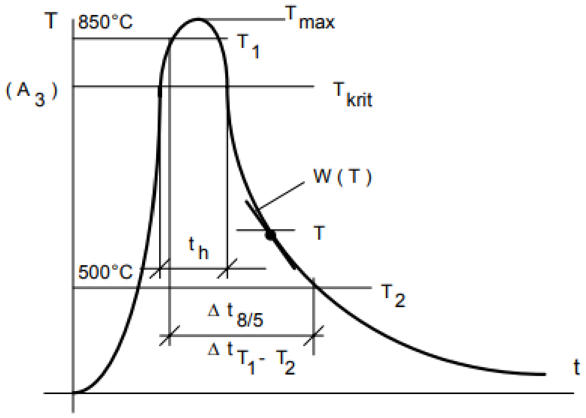

Fig. 1. Welding heat cycle [1]

The critical cooling time (measured in s) depends on the mode of heat conduction. In the case of three-dimensional heat dissipation, according to equation (1), the cooling time does not depend on the plate thickness (represented by "s" and measured in meters) (Yurioka, 2001):

$$\Delta t_{850-500} = \frac{(q/v)_{eff}}{2\pi\lambda}\left(\frac{1}{500-T_0} - \frac{1}{850-T_0}\right) \qquad (1)$$

For two-dimensional cooling, equation (2) gives the critical cooling time [2]:

$$\Delta t_{850-500} = \frac{(q/v)_{eff}^2}{\boldsymbol{4\pi\lambda c\rho} s^2}\left(\frac{1}{(500-T_0)^2} - \frac{1}{(850-T_0)^2}\right) \qquad (2)$$

According to equation (2), the cooling rate depends on the plate thickness. Whether the heat conduction is 2D or 3D depends on the critical plate thickness (s_{crit}, measured in meters) and is given by equation (3) (Yurioka, 2001):

$$s_{krit} = \sqrt{\frac{(q/v)_{eff}}{2c\rho}\left(\frac{1}{850-T_0} + \frac{1}{500-T_0}\right)} \qquad (3)$$

If the plate thickness (s) is greater than the critical plate thickness (s_{crit}), then the heat dissipation is 3D.

In the equations, [("q/v") _"eff"] represents the effective specific heat input (J/m), and it can be determined using equation (4) (Yurioka, 2001):

$$(q/v)_{eff} = \frac{UI\eta_{eff}}{v_{heg}} \qquad (4)$$

In the equations,

λ is the thermal conductivity coefficient (for steels, λ = 37…42 W/mºC),

T_0 is the preheating temperature (measured in °C),

cρ is the volumetric heat capacity (for steels, cρ = (5…5.2)10^6 J/m^{3o}C).

Regarding the equations, it should be noted that they are written for a point located in the plane of the weld, at the centre of the weld cross-section (Yurioka & Kasuya, 1995). In real cases, lower cooling rates occur, so deviating from the application of these equations provides a safety direction.

Analysing the equations, it can be observed that the critical cooling time becomes longer with an increase in the specific heat input, the application of preheating, and a thinner plate.

From equations (1) and (2), the expression for [("q/v") _"eff"] can be derived. This means that for a given critical cooling time, the specific heat input can be determined such that the smallest critical cooling time is achieved. Therefore, a cooling rate faster than the cooling rate corresponding to the critical cooling time does not occur. It also follows that if the critical cooling time is prescribed based on a mechanical criterion, such as hardness, when applying the calculated required specific heat input (or a higher heat input), a hardness greater than the prescribed hardness in the heat-affected zone will not be achieved.

Next, the paper reviews how the critical cooling time can be determined and what criteria can be used to specify its value.

The method for determining the required specific heat input and preheating temperature based on the critical cooling time was already included in the MSZ 6280 standard which equivalent to ISO 3834 (Palotás, 2015) (MSZ 6280 – 82, 1985). This standard contained the correlation between the carbon equivalent (C_e) associated with different hardness levels and the critical cooling time (Δt_{HV}) (Figure 3), as well as the determination of the specific heat input in the form of nomograms. Although the nomograms in the mentioned standard appendix were not accurate, they represented pioneering work as they were based on fundamental principles and introduced a new way of thinking, proving practical usability.

The equations describing the individual curves were also provided in the form of (Yurioka, 2001):

$$[\Delta tHV = a\ (Ce - C0)b] \qquad (5)$$

given at a 95% confidence level. The carbon equivalent is determined based on the recommendation of the IIW using a commonly known correlation (Yurioka, 2001):

$$Ce=C+ Mn/(6\ )+\ (Cr+Mo+V)/5+\ (Ni+Cu\ )/15 \qquad (6)$$

The constants corresponding to different hardness levels are as follows:

300 HV10 in the case of heat-affected zone hardness levels a= 432.5; b =1.87; C0 = 0.225

350 HV10 in the case of heat-affected zone hardness levels a = 291.5; b =1.66; C0 = 0.275

375 HV10 in the case of heat-affected zone hardness levels a = 283.9; b =1.56; C0 = 0.300

400 HV10 in the case of heat-affected zone hardness levels a = 214.1; b =1.40; C0 = 0.350.

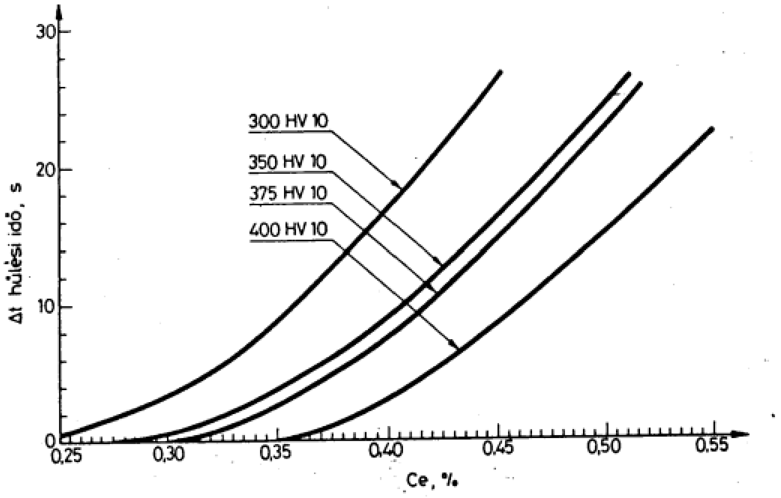

Fig. 2. Correlation between the critical cooling time and carbon equivalent at different hardness levels (Yurioka & Kasuya, 1995)

In Figure 2, these relationships are applicable only up to 0.50% carbon equivalent and up to a maximum of 0.55% even in the case of the highest hardness. This means that these relationships can only be applied to conventional, easily weldable steels (such as normalized steels with yield strengths of 235 MPa, 275 MPa, 355 MPa, 420 MPa, and 460 MPa). They are not applicable to the high-strength steels used today.

There is a need to establish relationships that can prescribe the maximum allowable hardness for various high-strength steels. The application of continuous cooling transformation diagrams taken for weldable steels seems suitable for this purpose. Examples of such diagrams are presented in Figure 3 and 4 (Bödök, 1997).

If we assume that we do not want martensitic microstructure in the heat-affected zone, based on the diagrams, we can determine the critical cooling time that can be prescribed. For KL 7 steel (currently designated as P355_), this value is 10 s, for 52D steel (S355J2+N) it is 7 s, for 12H1MF steel (low-alloy creep-resistant steel) it is 9 s, for 10 CrMo 9-10 steel (alloy creep-resistant steel) it is 25 s, and for H5M steel it is 18 s (this steel is a moderately alloyed creep-resistant steel with C = 0.14%, Cr ≈ 4.5%, Mo ≈ 0.5%). Beyond these estimated cooling times, other microstructures besides martensite start to form. The faster heating curves were considered in the analysis (Stroetmann et al 2018).

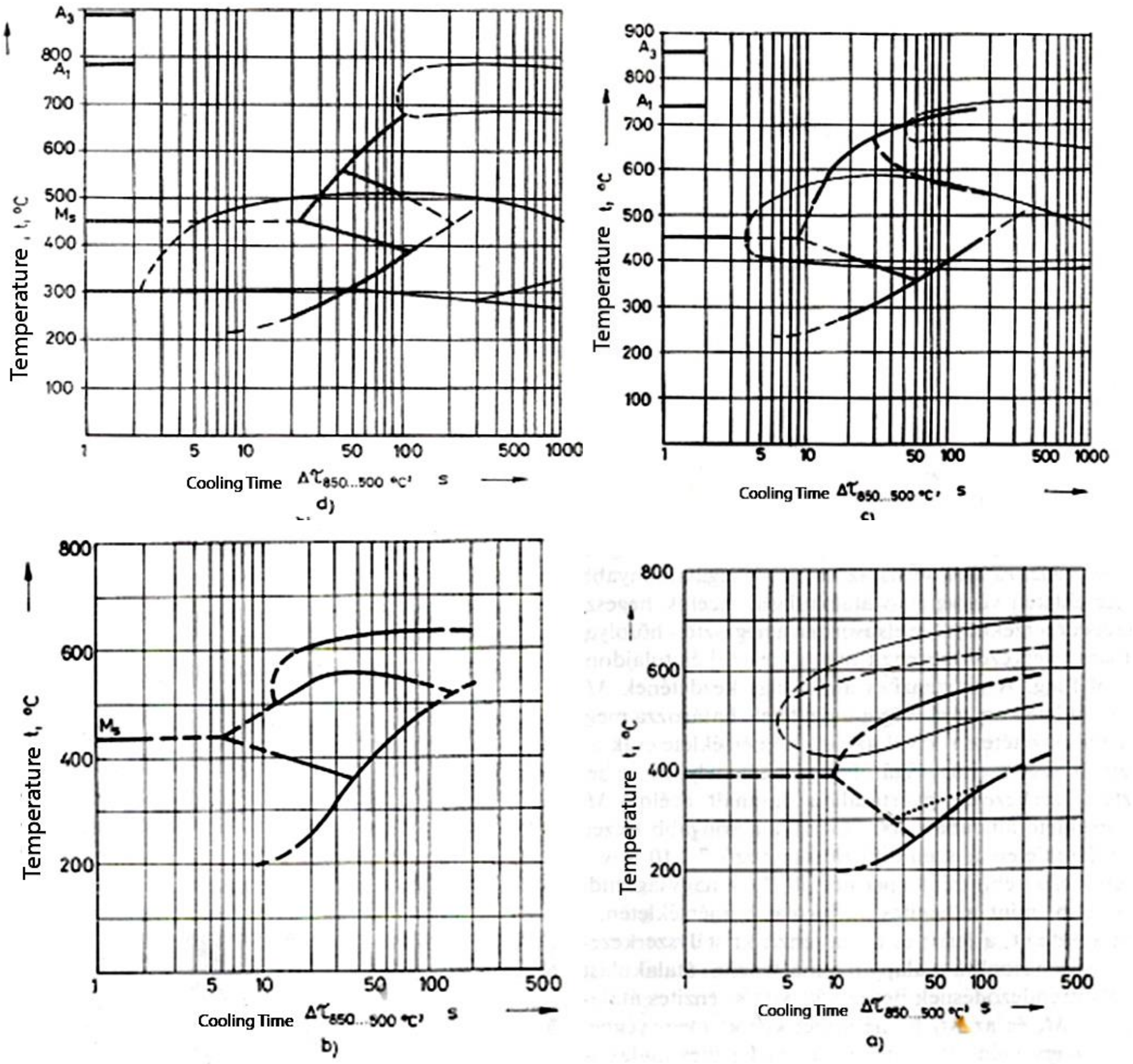

Fig.3. Transformation diagrams obtained through welding (Part 1) a. KL 7 steel b. 52D steel c. 12 H 1 MF steel d. 10 CrMo 9 10 steel (Thick line: [Wheat] = 250 °C/s, [tmax] = 1375 °C, [τ] = 0; Thin line: [Wheat] = 7 °C/s, [tmax] = 900 °C, [τ] = 300 s)

The presented correlations cannot be applied to the increasingly prevalent hardened and tempered steels (indicated by the supplementary letter Q, e.g., S690Q). They are also not applicable to steels produced through thermomechanical treatment (e.g., S960Msteel). If the critical cooling time for a specific steel is known, the presented equations (1), (2), (3), and (4) can be applied to determine the specific heat input that ensures crack-free welding, or if that cannot be achieved, the necessary preheating value. If we had access to continuous cooling diagrams for welding (like Figure 4, i.e., critical cooling time and corresponding temperature values along with the resulting microstructures), the critical cooling time could be determined, as shown earlier. However, recording transformation diagrams would require numerous measurements. Therefore, finding a simpler method for determining the critical cooling time would offer several technical and economic advantages.

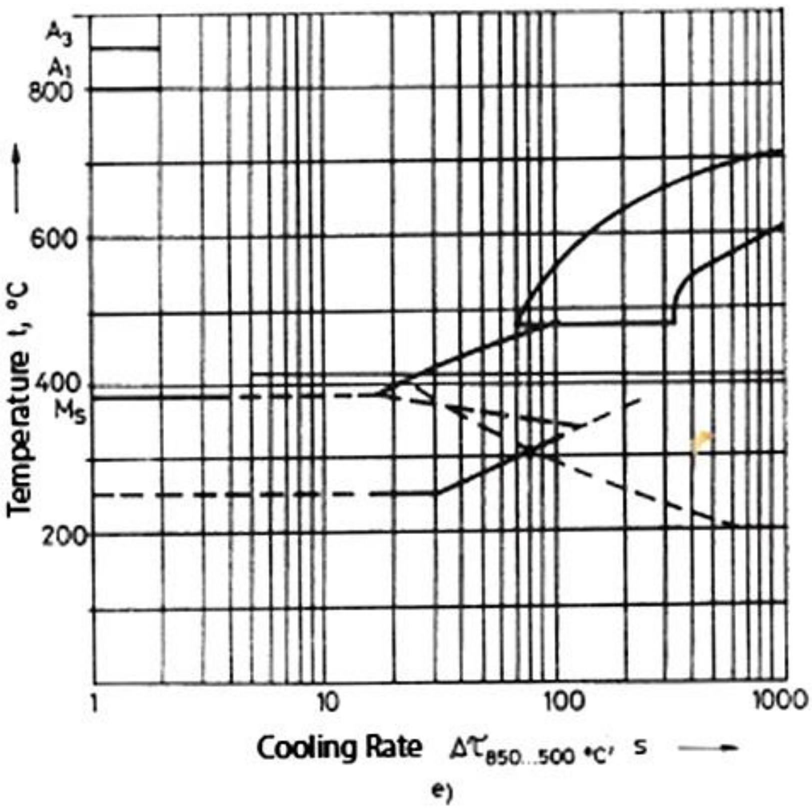

Fig.4. Transformation diagrams obtained by welding (Part 2)

e. H5M steel (Thick line: [Wheat] = 250 °C/s, [tmax] = 1375 °C, [τ] = 0; Thin line: [Wheat] = 7°C/s, [tmax] = 900 °C, [τ] = 300 s)

3. Determining the critical cooling time through measurement

I recommend using GLEEBLE physical simulators for determining the critical cooling time. The simulator can simulate identical thermal cycles throughout the entire cross-section of a test specimen, either in a vacuum or in a shielding gas environment. Both heating and cooling rates can be adjusted over a wide range. The simulator and the test specimen setup are illustrated in Figure 5 (Radaj, 1992).

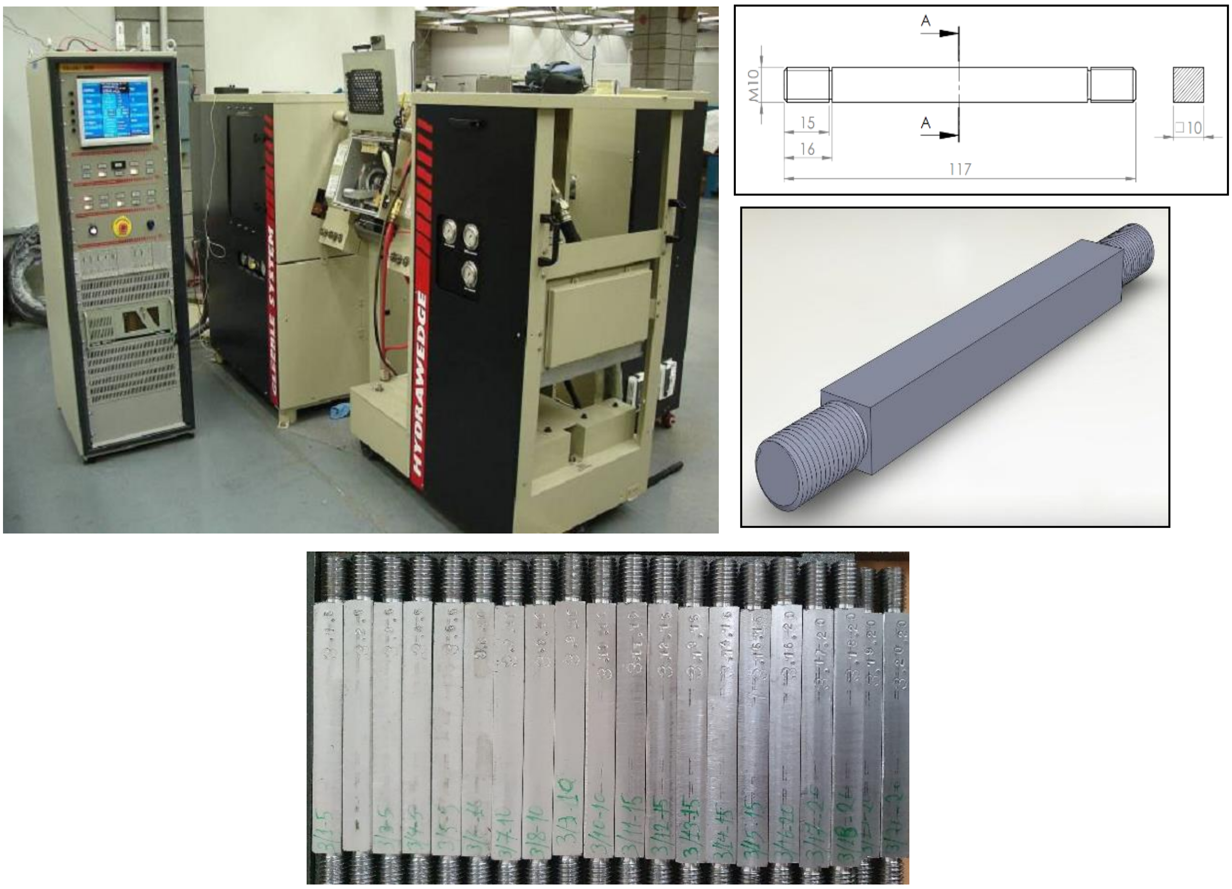

Fig.5. Image of the thermal process simulator and the test specimen and the prepared samples

I included thermo-mechanically treated steels in the thermal process modeling, namely S355MC, S500MC, S700MC, S960MC, and S1100MC. The cooling time was set to 5 s, 10 seconds, 15 seconds, and 20 seconds within the temperature range of 800°C to 500°C. The test specimens were rapidly heated to the austenitizing temperature (950°C ±20°C). Temperature regulation was performed using a thermocouple welded onto the center of the test specimen. The modeling was conducted using a GLEEBLE 3500 physical simulator located at the University of Miskolc. After that the Gleeble 3800 in university of Dunaújváros was repaired and I could repeat the simulation for two grades of my samples which were (S960MC, S1100MC) (Palotás, 2017). The applied thermal cycle is presented in Figure 6.

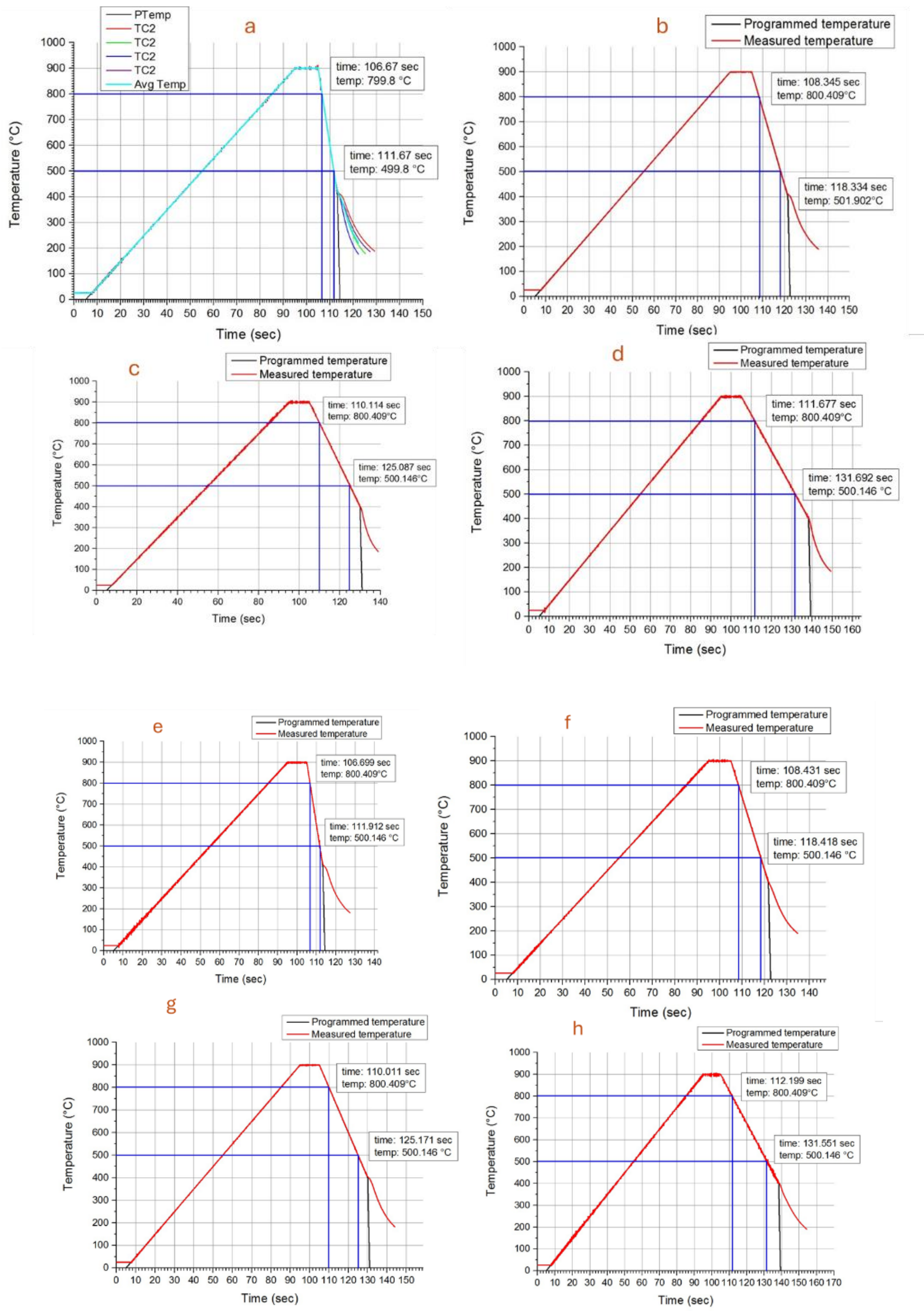

Fig.6. a: the applied thermal cycle in case of S960MC, 5sec summary for the five samples,

b: the applied thermal cycle in case of S960MC, 10Sec,

c: the applied thermal cycle in case of S960MC, 15sec,

d: the applied thermal cycle in case of S960MC, 20 sec

e: the applied thermal cycle in case of S1100MC,5sec,

f: the applied thermal cycle in case of S1100MC,10sec,

g: the applied thermal cycle in case of S1100MC,15sec,

h the applied thermal cycle in case of S1100MC,20sec

I chose the shape of the test specimen used for modeling in such a way that hardness measurements (at the center of the specimen on each plane) could be performed, and there was also the possibility of measuring impact energy. We had five test specimens made from each material and for each cooling time. With approximately 100 test specimens, a reliable evaluation can be carried out. The results of hardness measurements are illustrated in Figure 7. Results show the steel S355MC did not quenched no cases (this result is coherent with result found in (Palotás, 2017).

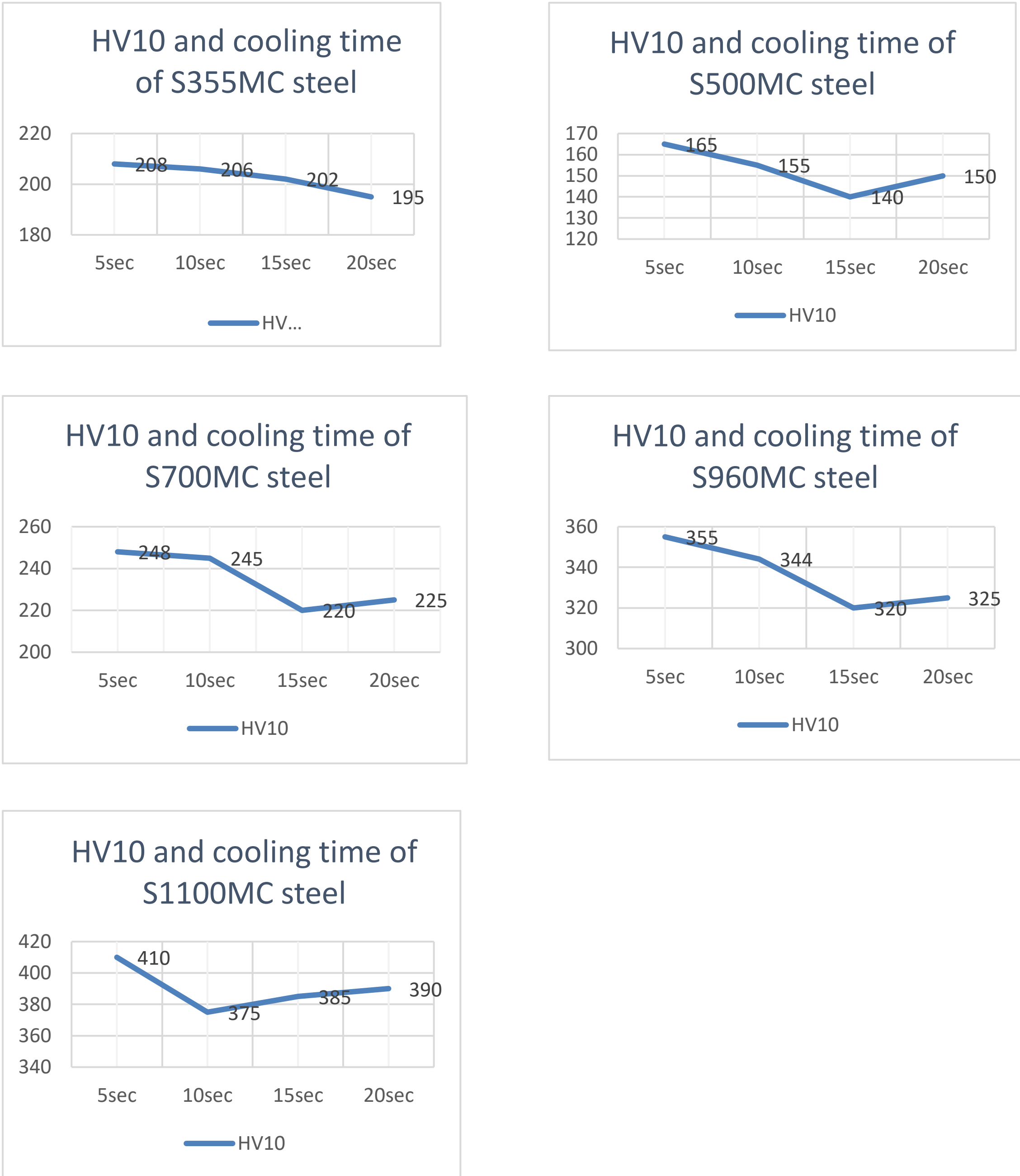

Fig.7. the relation between the cooling time and the hardness results for all the grades materials

Based on these diagrams, we can determine the required cooling time based on my findings. This information is crucial for accurately determining the preheting temperature for materials such as S355MC, S500MC, S700MC, S960MC, and S1100MC. By extracting the cooling time value from the graph and integrating it into the equations mentioned earlier, we can ascertain the appropriate preheating temperature for these materials.

To make the calculation more accurate I create a C++ program to give the preheating temperature according to the carbon content and the cooling time.

This program takes input for cooling time (in seconds) and carbon content (in percentage), calculates the preheating temperature based on the provided formula, and outputs the result. You can use this program directly without any modification. However, please note that you may need to adjust the constants in the formula (constant1 and constant2) based on the specific formula you are using for preheating temperature calculation. See the Appendix A.

4. Conclusion

The study focuses on a practical method for determining the preheating temperature in steel welding through hardness testing and graphical representations of cooling time. Cold cracking in welding is a serious defect that can be avoided by preheating high-strength steels. The use of a carbon equivalent as a weldability indicator is proposed, with preheating being the most effective way to prevent cold cracking. The study introduces a simplified methodology using a C++ program that calculates preheating temperature based on specific parameters. By conducting tests on various thermal process models of high-strength steels and analyzing hardness values at different cooling times, the study provides insights into determining the optimal preheating temperature for welding. The critical cooling time can be determined using specialized equipment like the GLEEBLE simulator, and the results can be used to calculate the required preheating temperature accurately. By developing a C++ program, the study offers a practical tool for welders to determine the preheating temperature based on the carbon content and cooling time, enhancing the quality and integrity of welds.

Acknowledgements

I would like to express my deepest gratitude to my supervisor Palotás Béla Dr. habil for his invaluable guidance and support throughout this project. His insights and feedback have been instrumental in shaping the development of this work. I also wish to acknowledge Dr. habil.

Marcell Gáspár, associate professor and head of the Institute of Material Science and Technology, Department of Structural Integrity, Faculty of Mechanical Engineering and Informatics at the University of Miskolc, for his support in completing the tests with the Gleeble 3500.

Additionally, I am grateful for the support of Dr. habil. Attila Kővári at the University of Dunaújváros and my workplace located at the University of Dunaújváros for providing access to the laboratories needed to complete the mechanical tests and the Gleeble 3800.

References

Abdulkareem, S. A., & Abboud, A. J. (2021, February). Evaluating Python, C++, JavaScript and Java programming languages based on software complexity calculator (halstead metrics). In IOP Conference Series: Materials Science and Engineering (Vol. 1076, No. 1, p. 012046). IOP Publishing.

Bödök, K. (1997). Corrosion resistance of unalloyed, low-alloyed, and high-alloyed structural steels, with special focus on their weldability. Corweld Ltd. publication.

Dale, N. B., & Weems, C. (2004). Programming in C++. Jones & Bartlett Learning.

Hubbard, J. R. (2021). Programming with C++.

Kou, S. (1987). Welding metallurgy. John Wiley and Sons.

Kvackaj, T., Bidulská, J., & Bidulský, R. (2021). Overview of HSS steel grades development and study of reheating condition effects on austenite grain size changes. Materials, 14(8), 1988.

MSZ 6280 - 82. (1985). Steels for welded structures. National Standard of the Hungarian People's Republic.

Palotás, B. (2017). Modeling of welding heat processes using GLEEBLE 3800 physical simulator. Scientific Presentation at Széchenyi István University, Győr.

Palotás, B. (2015). Weldability of fine-grained steels. MAGÉSZ Steel Structures, 12(2), 59-67.

Radaj, D. (1992). Heat effects of welding. Springer-Verlag.

Stroetmann, R., Kästner, T., Hälsig, A., & Mayr, P. (2018). Influence of the cooling time on the mechanical properties of welded HSS-joints. Steel Construction, 11(4), 264-271.

Sun, J., & Dilger, K. (2023). Influence of preheating on residual stresses in ultra-high strength steel welded components. Journal of Materials Research and Technology, 25, 3120-3136.

Yurioka, N. (2001). ISIJ International, 6, 566-570.

Yurioka, N., & Kasuya, T. (1995). Welding in the World, 5, 31-38.

About Authors

Lama Mkanna received her M. Sc. degree in Mechanical Engineering from University of Dunaújváros in 2020 and currently a PhD student in Széchenyi István University, Doctoral School of Multidisciplinary Engineering Sciences, Transportation and vehicle engineering. She is a teacher assistant at University of Dunaújváros, she is giving lectures and supervising the students with their thesis. Her research interests include weldability and avoiding the cold cracking for the HSS, the importance of the HSS in the vehicle industry.

Appendix A

```
#include <iostream>
using namespace std;

// Function to calculate preheating temperature
double calculatePreheatingTemperature(double coolingTime, double carbonContent) {
    // Constants for calculation
    const double constant1 = 50;  // Modify this constant based on your formula
    const double constant2 = 0.8;  // Modify this constant based on your formula

    // Convert cooling time from seconds to minutes
    coolingTime /= 60.0;

    // Formula for calculating preheating temperature
    double preheatingTemperature = constant1 * coolingTime + constant2 * carbonContent;
    return preheatingTemperature;
}

int main() {
    // Input parameters
    double coolingTimeInSeconds; // Cooling time in seconds
    double carbonContent;        // Carbon content in the steel (percentage)

    // Get user input
```



```
    cout << "Enter cooling time (seconds): ";
    cin >> coolingTimeInSeconds;
    cout << "Enter carbon content (%): ";
    cin >> carbonContent;

    // Calculate preheating temperature
    double preheatingTemperature = calculatePreheatingTemperature(coolingTimeInSeconds,
carbonContent);

    // Output result
    cout << "Preheating temperature for welding HSS: " << preheatingTemperature << " °C" <<
endl;
    return 0;
}
```

