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Practice-based determination of preheating temperature by Tekken test for welding of high strength steels

Az előmelegítési hőmérséklet gyakorlati úton történő meghatározása Tekken vizsgálattal nagyszilárdságú acélok hegesztéséhez

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Abstract: *This study builds upon a previously developed method for calculating optimal preheating temperatures in steel welding, which was initially based on hardness testing and graphical analysis of cooling times to prevent cold cracking. In this follow-up, the methodology is expanded by incorporating critical cooling times derived solely from instrumented Charpy impact tests, providing additional insights into material toughness and crack resistance. Using these values, preheating temperatures were calculated for various S960MC and S1100MC through a simplified Python program that accounts for critical cooling time and test plate dimensions. The calculated preheating temperatures were then applied in Tekken tests to evaluate their impact on weld quality and resistance to cracking. Results showed a strong correlation between the calculated preheating temperatures and improved crack resistance, validating both the accuracy and practical applicability of the refined approach. This integrated method significantly enhances weld quality and structural integrity, underscoring its value for high-strength steel welding applications.*

Absztrakt: *Ez a tanulmány egy korábban kidolgozott módszerre épül, amely az optimális előmelegítési hőmérsékletek meghatározását szolgálja acélok hegesztése során, eredetileg keménységvizsgálatra és hűlési idő grafikus elemzésére alapozva, a hidegrepedés elkerülése érdekében fejlesztették ki. Ebben a cikkben a módszertant továbbfejlesztették, műszerezett ütővizsgálatokból származó kritikus hűlési idő értékek beépítésével, amelyek további betekintést nyújtanak az acél szívósságába és repedésállóságába. Ezen értékek alapján S960MC és S1100MC anyagminőségek esetében meghatároztam az előmelegítési hőmérsékleteket egy egyszerűsített Python program segítségével, amely figyelembe veszi a kritikus hűlési időt és a vizsgálati lemezek méreteit. A számított előmelegítési hőmérsékleteket ezt követően Tekken vizsgálatnak vetettem alá annak értékelésére, hogy miként befolyásolják a hegesztés minőségét és a repedésállóságot. Az eredmények erős korrelációt mutattak a számított előmelegítési hőmérsékletek és a fokozott repedésállóság között, igazolva ezzel a továbbfejlesztett megközelítés pontosságát és gyakorlati alkalmazhatóságát. Ez az integrált módszer jelentősen javítja a hegesztés minőségét és a szerkezeti integritást, kiemelve annak fontosságát a nagyszilárdságú acéloknál.*

Keywords: *Preheating temperature, Tekken test, Instrumented Charpy impact test, Hardness-cooling relationship, Cooling time optimization, Material performance.*

1. Introduction

Cold cracking, also known as hydrogen-induced cracking, is a critical defect in steel welding, typically occurring at temperatures below 200 °C. Often called "delayed cracking" due to the incubation period required for crack formation, cold cracking results from the simultaneous presence of diffusible hydrogen in the weld metal, a microstructure susceptible to cracking, and residual stresses. This phenomenon is most prevalent in the heat-affected zone (HAZ) of high-strength steels, where the risk is heightened due to the material's structural sensitivity and mechanical properties under thermal stress [1]. Historically, various factors, including weld metal strength, hydrogen content, microstructure, restraint, and cooling rate, have been identified as influential in cold cracking formation, with preheating recognized as the most effective method to mitigate it. By slowing the cooling rate and reducing hardness within the HAZ, preheating can significantly lower the likelihood of cold cracking [2].

Correctly determining the preheating temperature is critical in achieving effective crack prevention, as insufficient preheating can leave the weld susceptible to cracking. This study expands on prior work that introduced a Python-based program for calculating optimal preheating temperatures. The program takes into account steel composition (notably carbon and manganese content), material thickness, and welding speed, employing predefined coefficients to calculate the required preheating temperature. Previous research applied a simplified approach using graphical representations based on hardness testing, derived from Gleeble 3500 simulations that modeled the thermal behavior of thermo-mechanically treated steels [3]. These simulations evaluated cooling times ranging from 5 to 20 seconds between 800 °C and 500 °C in high-strength steels such as S355MC, S500MC, S700MC, S960MC, and S1100MC [4].

Building on these findings, this follow-up study applies calculated preheating temperatures to Tekken tests on S960MC and S1100MC high-strength steels to assess weld quality and susceptibility to cold cracking. In line with previous results indicating that preheating is not essential for lower-strength steels such as S355MC, S500MC, and S700MC, the focus here remains on higher-strength grades [5]. Additionally, instrumented Charpy impact tests were performed to evaluate material toughness, providing further insights into the relationship between hardness values, cooling times, and preheating temperatures. This expanded approach demonstrates the effectiveness of targeted preheating in improving weld quality and crack resistance for high-strength steels, reinforcing its practical applicability in welding applications [6,7].

2. Experimental materials and equipment

2.1. Material properties

The tests are including physical simulation with the Gleeble (3500, 3800), hardness test, instrumented Charpy impact test and Tekken on two materials with different grades S960MC, S1100MC. Table 1 shows the chemical compositions of the S960MC and Table 2 shows the chemical compositions of S1100MC, while Table 3 shows the mechanical compositions of the two materials.

Table 1. Chemical composition of S960M steel, wt%

C	Si	Mn	P	Cr	Ni	Mo	V	Ti	Cu	Al	Nb	B
0.16	0.20	1.22	0.011	0.20	0.05	0.605	0.037	0.002	0.01	0.055	0.015	0.001

Table 2. Chemical composition of S1100M steel, wt%

C	Si	Mn	P	Cr	Ni	Mo	V	Ti	Cu	Al	Nb	B
0.13	0.32	1.62	0.009	0.63	0.32	0.62	0.066	0.011	0.047	0.035	0.037	0.0014

Table 3. Thickness and mechanical properties of the examined steels

Material grade	Thickness [mm]	$R_{p0,2}$ [MPa]	R_m [MPa]	A [%]	KV -40 °C [J]
S960M	10	1027	1058	15	87
S1100M	15	1193	1221	11.6	88

2.2. Instrumented Charpy impact test

The instrumented Charpy impact test was conducted at -40 °C according to the standard EN ISO 14556 [8] using Charpy cool equipment to simulate the extreme conditions that contribute to cold cracking in high-strength steels. S960 MC and S1100 MC steel samples were tested, with 20 specimens for each material. The samples were divided into four groups of five samples, each group corresponding to a different cooling time (5 s, 10 s, 15 s, and 20 s), applied using the Gleeble 3800 simulator. This test aimed to evaluate the toughness of the materials under controlled cooling conditions and examine how different cooling times influence the resistance to cracking at low temperatures (see Figure 1 and 2). Table (4) shows the average measured impact energy results where five specimens were examined for each cooling time, and Table 5 and 6. show the crack propagation.

Figure 1. Charpy impact tester

Figure 2. Specimens after the instrumented Charpy impact tests

Table 4. *CVN results*

Material grade	CVN [J] $t_{8/5} = 5$ s	CVN [J] $t_{8/5} = 10$ s	CVN [J] $t_{8/5} = 15$ s	CVN [J] $t_{8/5} = 20$ s
S960M	69	37	58	45
S100M	70	53	35	18

Table 5. *Crack propagation ratio of S1100M*

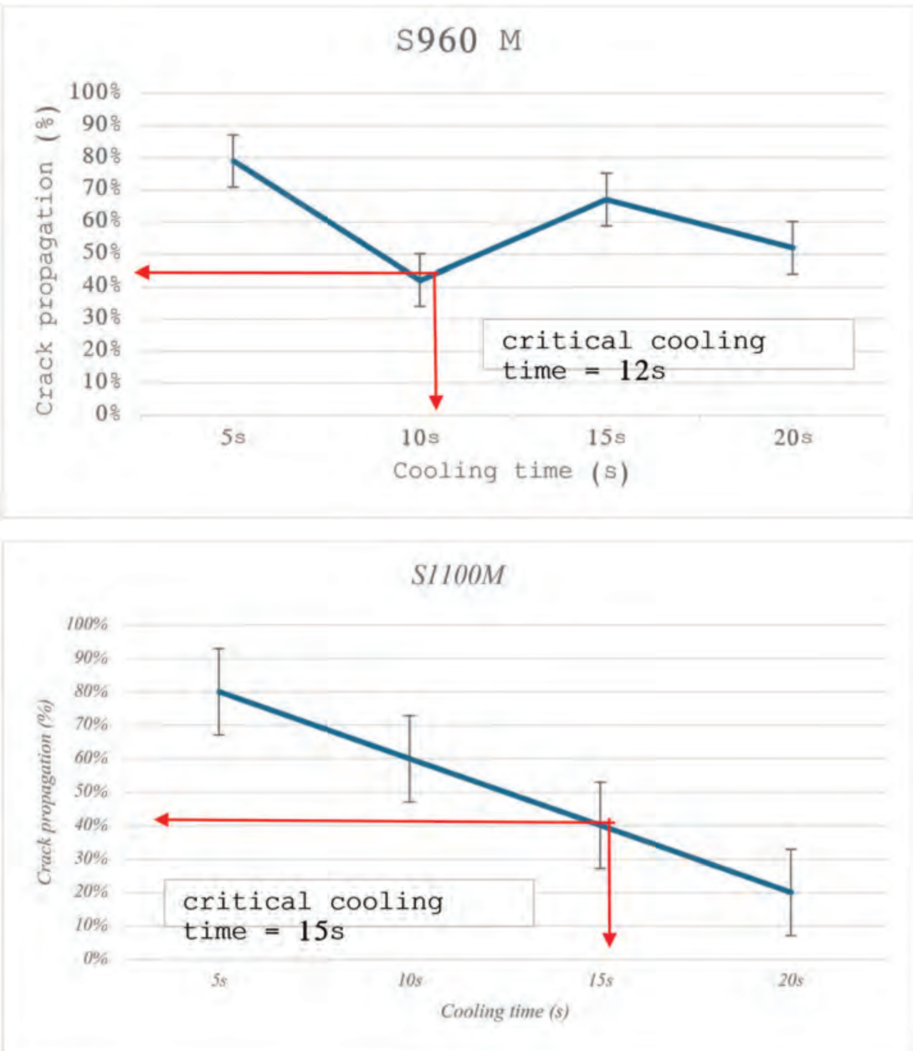
Cooling time	Crack propagation
5 s	80%
10 s	60%
15 s	40%
20 s	20%

Table 6. *Crack propagation ratio of S960M*

Cooling time	Crack propagation
5 s	79%
10 s	42%
15 s	67%
20 s	52%

After the impact test, crack propagation was analyzed by inspecting the fracture surfaces of the specimens according to the impact energy values and the instrumented Charpy results. The extent of crack growth was evaluated to determine the influence of each cooling time on the material's ability to resist brittle fracture. After that diagram was created to assist determining the cooling time. This diagram shows the relation between the percentage of the absorbed energy for crack propagation and the cooling time and when the percentage is less than 50% it means it is a brittle failure and this where we can consider it a critical cooling time. For S960M steel, as shown in the graph, the highest crack propagation occurred at a cooling time of 10 s. Based on the analysis, the critical cooling time for S960M steel was determined to be approximately 12 s, as this time correlated with minimal crack growth, and in the case of S1100M steel, the critical cooling time was determined to be 15 s (see Figure 3.)

This graphical representation of crack propagation versus cooling time was essential for identifying the optimal cooling conditions to improve material toughness. The critical cooling time data was then used to calculate the appropriate preheating temperature for welding applications, ensuring a reduced risk of cold cracking.



3. Figure The relation between the cooling time and the crack propagation

2.3. Calculation of the preheating temperature for welding applications

Following the determination of the critical cooling time from the previous diagrams, I substituted these values into the Python program developed for calculating preheating temperatures. For S1100 steel, the program yielded a preheating temperature T_0 = 150 °C, while for S960 steel, the calculated preheating temperature was T_0 = 125 °C.

These calculated preheating temperatures are essential for optimizing the welding process, as they help minimizing the risk of cold cracking and enhancing the overall quality of the welds. By maintaining these preheating temperatures during welding, the cooling rates can be controlled more effectively, thereby reducing residual stress and improving the mechanical properties of the welded joints. The integration of critical cooling time data into the calculation process demonstrates the practical applicability of the method, providing a reliable approach to ensuring the structural integrity of high-strength steel weldments [4].

See Appendix A to see the codes.

3. Tekken test

In the welding process, multiple weld runs were performed using different techniques and parameters to achieve optimal joint quality. The initial weld run (Run 1) was carried out using the 111 processes (manual metal arc welding) with a 4 mm diameter E46 5 B filler metal electrode. This run used direct current (DC) with a current range of 150-160 A and a voltage between 25-26 V. Subsequent weld runs (Runs 2-4) also utilized the 111 processes but with a larger, 5 mm diameter E46 5 B electrode. These runs operated at a higher current range of 200-220 A and a voltage between 30-32 V. The final weld run (Run 5) employed the 135 process (metal active gas welding, MAG) using a 1 mm diameter G 89 5 M filler metal with a DC+ polarity. This run was performed at a current range of 170-190 A, with a voltage of 23-24 V, a travel speed of 200 mm/min, and a calculated heat input between 0.9 and 1.08 KJ/cm.

The Tekken test was conducted to evaluate the weld quality and assess the susceptibility of S960M and S1100M steels to cold cracking, following the mathematical determination of preheating temperatures. This standardized method, following ISO 17642-2, involves subjecting welded specimens to tensile forces to observe the material's response under stress. For each grade, two samples were prepared: one set was preheated to 150 °C for S1100 and 125 °C for S960, the preheating process was performed in a furnace for the materials and the electrodes as well for approximately 2 hours, while the other set was tested without preheating. During the testing process, the welded joints were closely monitored for any signs of cracking. The results indicated that the non-preheated specimens exhibited both hot cracking and cold cracking, particularly due to inadequate temperature control during the welding process. In contrast, the preheated specimens showed significantly higher resistance to crack formation, demonstrating the effectiveness of proper preheating in preventing cold cracking. The outcomes of this study provide critical insights into the impact of preheating on the mechanical properties of welds. The data indicates a strong correlation between preheating temperatures, weld quality, and crack propagation behavior. This information is invaluable for optimizing welding procedures for high-strength steels, ensuring the structural integrity of welded components. The successful application of preheating temperatures, as confirmed by the Tekken test results, reinforces the necessity of adhering to standard procedures to minimize the risk of cold cracking and enhance weld quality. [10-15].

Figure (4) illustrates the configuration and dimensions of the specimens, under the ISO 17642-2 standard.

The welding parameters used for both S960 and S1100 materials are detailed in Table 8.

These standardized welding parameters ensured the consistency of the testing process, supporting the analysis of how preheating affects weld integrity and resistance to cold cracking in high-strength steels.

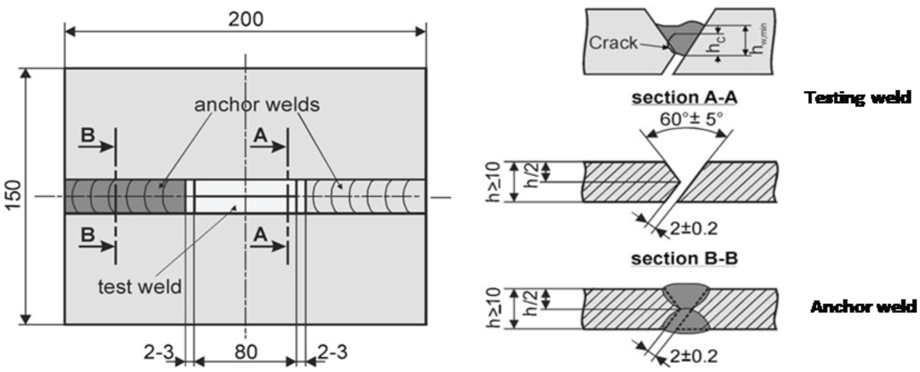


Figure 4. Configuration and dimensions [16]

Table 8. *Welding parameters*

Weld Runs	Process	Filler Metal		Current			Voltage, V	Travel speed[1]	Heat Input KJ/cm[1]
		Classification	Diameter	Type	Range, A				
1	111	E46 5 B	4 mm	DC	150	160	25 -26	N/A	
2 - 4	111	E46 5 B	5 mm	DC	200	220	30 - 32	N/A	
5	135	G 89 5 M	1 mm	DC+	170	190	23 -24	200 mm/min	0.9 – 1.08

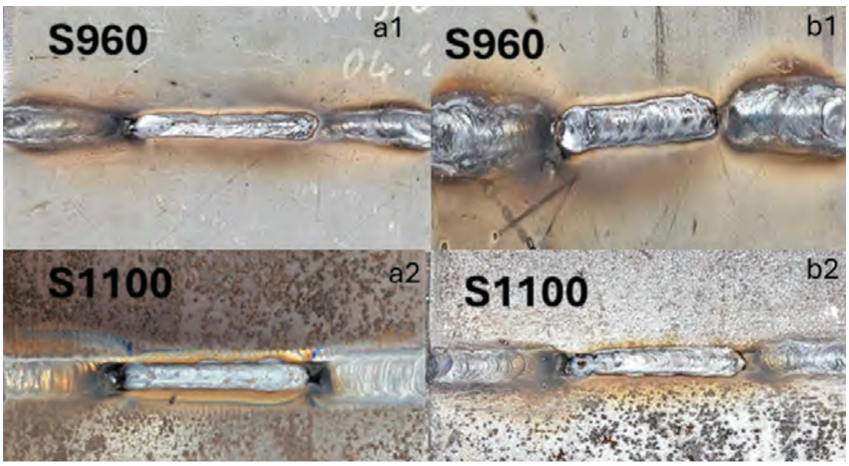


Figure 5. The a1 and a2 the welded joints without preheating, b1 and b2 the welded joints with preheating

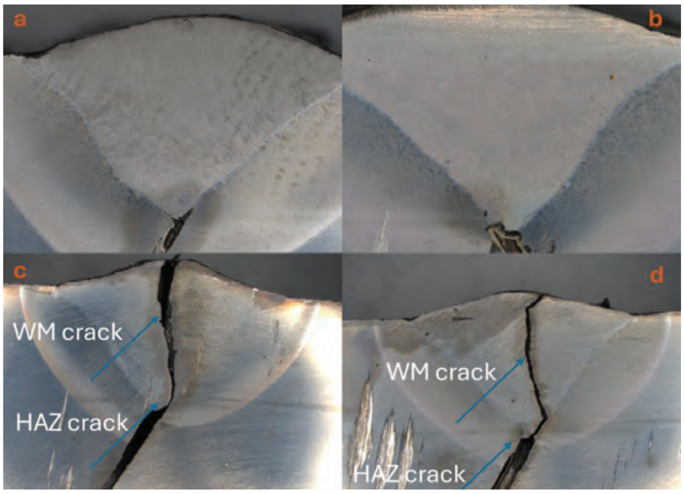


Figure 6. Microscope image of the cross section of S960M where a and b were preheated before the welding, and c and d were not preheated

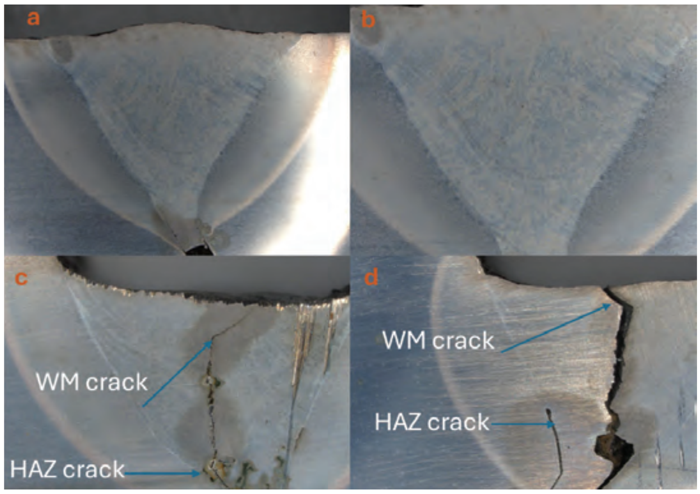


Figure 7. Microscopic image of the cross section of S1100M where a and b were preheated before the welding, and c and d were not preheated

Figure (5) shows the welded joints, the thickness of the plates for S960 is equal to 10 mm, and for S1100 equals 15 mm.

After exposure and cooling of the specimens for 48 hours, slice samples of each of the specimens were made for microstructure investigation by using the 3D dimensional microscope device to determine the formation of cracks with magnification 30. This feature helped to assess internal structure in detail, as it is presented in Figure 6. and 7.).

On the non-preheated samples, weld bead cracks were deeply noticeable by the naked eye. Further analysis of the cross-sections showed that cracks initiated in the HAZ and spread towards the fusion zone FZ.

4. Conclusion

In conclusion, the facts derived from this research, alongside those established from prior research, confirm that despite the superior strength and toughness of developed high-strength steels (HSS), steels with strength greater than S700 are more susceptible to cold cracking. This vulnerability poses a major problem especially in welding applications where material properties and resistance to crack are crucial. To avoid the possibility of cold cracking in the above higher grade steels, enough preheating is required. Preheating slows the cooling rate of the weld zone which reduces residual stress in addition to reducing the formation of hard brittle microscopic regions that cause crack formations.

Also, if hardness measurements are used for assessing critical cooling time, the instrumented Charpy impact test provides the ability to increase the accuracy in establishing preheat temperatures. This test goes a long way in establishing crack resistance as well as material toughness and therefore, a better examination of the performance of steel under different cooling rates. Using the empirical formulas to calculate the preheating temperatures, there are other methods like hardness-based methods. However, the most suitable method that is accurate is the instrumented Charpy test based on standard EN 10045-1. This order, when implemented to its capacity, allows engineers and welders to fix preheating temperatures hence control weld quality and structural soundness. In the end, the instrumented Charpy impacr test for preheating temperature determination of preheating provides for a reliable means of enhancing crack resistance and optimize welding process on high-strength steel.

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Appendix A

Here is the code in the case of S1100 with 15mm thickness and for other HSS materials it needs to modify the input parameters.

```
import math
# Define the  equation to be solved
def equation(T_0, q_v_eff, Δt_850_500, λ, cρ, s):
    term1 = (q_v_eff **  2) / (4 * math.pi * λ * cρ * s ** 2)
    term2 = (1 / (500 - T_0) ** 2) - (1 / (850 - T_0) ** 2)
    return term1 * term2 - Δt_850_500
# Manual iterative solver for T_0
def calculate_T_0(q_v_eff, Δt_850_500, λ, cρ, s):
    initial_guess = 50 # Start with an initial guess of 200°C
    tolerance = 0.001  # Define how close the solution needs to be
    max_iterations = 1000  # Limit iterations to avoid infinit e loops
    T_0 = initial_guess

    for _ in range(max_iterations):
        result = equation(T_0, q_v_eff, Δt_850_500, λ, cρ, s)

        if abs(result) < tolerance:  # If the result is close enough to
zero, break the loop
            break
        T_0 += 0.1  # Adjust the guess (step size is 0.1°C for this
example)
    return T_0
# Input values
q_v_eff =   1.6896  # KJ/mm
q_v_eff_m3 = q_v_eff *   10 ** 9  # Convert to J/mm
Δt_850_500 = 15  # seconds
λ = 30  # W/m°C
cρ = 3_689_500  # J/m³°C, volumetric specific heat for HSS 960
s = 0.15  # meters (15 mm)
# Calculate T_0
T_0 = calculate_T_0(q_v_eff_m3, Δt_850_500, λ, cρ, s)
# Print the result
print(f"T_0 = {T_0:.2f} °C")
T_0 = 150.00 °C
```