



Original research article

Influence of Peak Temperature on the Hardness in the Heat Affected Zone of S700MC, CK45 and S355W Welds

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ABSTRACT

Welding of carbon steels induces significant microstructural modifications within the heat-affected zone (HAZ), which influence the material's performance during service. These changes are typically associated with increased hardness and reduced toughness. Although often remaining within acceptable limits, they must still be considered, especially when the weld is part of a highly demanding application.

Continuous Cooling Transformation (CCT) diagrams, which are typically used to describe heat-treatment behaviour, are not fully suitable for welding applications. This is because welding heat cycles differ substantially from quenching: they reach much higher temperatures and include no soaking time. As a result, HAZ hardness depends not only on the cooling rate but also on the heating rate and the peak temperature reached at each point within the HAZ. These parameters govern the transformation of pearlite into austenite and the homogenization of the austenitic phase.

This paper investigates the influence of the peak temperature within the HAZ on the hardness of three different steels (S355, C45, and S700MC) under conditions of relatively slow cooling. Samples were heated in a furnace to predefined maximum temperatures and then immediately cooled in an air stream. The results indicate that, beyond a certain temperature, a sharp transition from low to high hardness occurs. This transition is associated with grain coarsening and completion of the austenitization process. Compared to oil quenching, additional features such as the formation of Widmanstätten microstructures were also observed.

Key words: Welding, steel, heat affected zone, hardening, overheating, CCT diagram, Widmanstätten.

1. INTRODUCTION

In welding, the heat-affected zone (HAZ) refers to the portion of the base material that does not melt but undergoes microstructural changes due to exposure to a thermal cycle. Each point within the HAZ surrounding the weld bead experiences a distinct thermal cycle depending on its distance from the fusion line, where the material

reaches the melting point. The closer a point is to the fusion line, the higher the peak temperature it experiences, the more intense the thermal cycle, and consequently, the greater the microstructural changes.

This gradual variation in HAZ microstructure, from the fusion line to the unaffected base metal, is accompanied by a corresponding change in mechanical properties. However, in carbon steels, this transition is not entirely gradual. A

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distinct discontinuity occurs once the material reaches temperatures high enough to cause austenitization. Near the fusion line, this transformation is unavoidable, and during subsequent rapid cooling the material may undergo quenching, resulting in the formation of undesirable, excessively hard and brittle phases. For this reason, controlling hardness within the HAZ is critical, and welding standards specify maximum allowable values that must not be exceeded.

When necessary, an initial estimation of the hardness a material may reach in the HAZ can be made based on its carbon content [1], using equations such as the Yurioka equation [2] or, preferably, continuous cooling transformation (CCT) diagrams that also account for the cooling rate. However, CCT diagrams are typically constructed for thermal cycles in which a relatively low austenitization temperature is reached and held for a certain period until complete austenitization occurs.

The welding thermal cycles differ significantly from those represented in conventional CCT diagrams, primarily because welding involves no soaking time and reaches much higher peak temperatures. The absence of a soaking period means that the required phase transformations cannot rely on time at temperature; instead, higher temperatures must compensate for this, and full austenitization is often not achieved at the expected temperature [3], [4]. Additionally, the total heat input delivered to the material depends strongly on the heating rate. At the same time, the very high peak temperatures reached within certain regions of the HAZ cause severe grain coarsening and alter the material's behaviour during cooling, including the possible formation of Widmanstätten microstructures [5].

Although the effects of heating rate and peak temperature have been investigated for several steels in [4], the available data correspond only to cooling rates above the critical one and are therefore not directly applicable to welding conditions. This limitation makes accurate prediction of the resulting HAZ microstructure difficult. While this uncertainty may be acceptable in less demanding applications, high-performance components require precise knowledge of the weld properties. This is also crucial for finite-element simulations, as the mechanical behaviour within the HAZ differs substantially from that of the original base material.

This paper presents the results of a research study designed to replicate HAZ thermal cycles at various distances from the fusion line in three steels: S355, C45, and S700MC, in order to systematically investigate the influence of peak temperature on hardness. To achieve this, samples were heated in a furnace to predetermined maximum temperatures and then immediately cooled under controlled air flow, simulating realistic welding cooling rates. This methodology enables a systematic assessment of the relationship between thermal exposure, microstructural evolution, and hardness, providing insight into critical temperature thresholds relevant for welding practice and modelling.

2. MATERIALS AND METHODS

2.1 Materials

To investigate the influence of peak temperature at different locations within the heat-affected zone (HAZ) on the hardness of welded carbon steels, three steels were selected: S355, C45, and S700MC. All steels were supplied in the form of 3-mm-thick plates, providing uniform geometry for controlled heating cycles and enabling a direct comparison of their responses to thermal exposure. S355 (EN 10025-2) is a mild structural steel widely used in construction and general engineering due to its good weldability and machinability. Owing to its low carbon content, the formation of hard microstructural constituents in the HAZ is not expected under typical welding conditions. Its chemical composition and mechanical properties are presented in Tables 1 and 2.

Table 1. Chemical composition of S355 [mass %]

C	Si	Mn	Cu	Ceq
0.078	0.4	1.0	0.3	0.39

Table 2. Mechanical properties of S355 steel

Tensile strength (MPa)	Yield strength (MPa)	Ultimate strain (%)	Hardness (HV)
560	452	29	180

C45 steel (EN 683-1) is a medium-carbon steel commonly used for the production of shafts and other mechanical components due to its combination of strength, toughness, and wear resistance. Its relatively high carbon content limits weldability, making preheating, hydrogen removal, or post-weld heat treatment strongly recommended. The chemical composition and mechanical properties of C45 steel are provided in Tables 3 and 4.

Table 3. Chemical composition of C45 [mass %]

C	Si	Mn
0.478	0.24	0.79

Table 4. Mechanical properties of C45 steel

Tensile strength (MPa)	Yield strength (MPa)	Ultimate strain (%)	Hardness (HV)
792	498	19.5	201

S700MC (EN 10149-2) is classified as a high-strength low-alloy (HSLA) structural steel, with its mechanical properties predominantly governed by the fine-grained microstructure produced through thermomechanical processing. Despite its favourable weldability resulting from low carbon content, the application of welding heat input can lead to grain coarsening within the HAZ and corresponding degradation of mechanical properties. The chemical composition and mechanical characteristics of this steel are given in Tables 5 and 6.

Table 5. Chemical composition of S700MC [mass %]

C	Mn	Si	Cr	Nb	V	Ti
0.06	1.86	0.026	0.03	0.07	0.0055	0.124

Table 6. Mechanical properties of the S700MC steel plate

Tensile strength (MPa)	Yield strength (MPa)	Ultimate strain (%)	Hardness (HV)
560	452	29	180

2.2 Samples preparation

For each steel type, 10 mm wide specimens were cut from the original 3 mm thick plates. Each specimen was drilled with a 0.9 mm hole to allow insertion of the thermocouple tip for temperature monitoring.

Heating was performed in a furnace to peak temperatures between 850 and 1250 °C, with the furnace set 50 °C above the target temperature. The heating rate was intentionally lower than that experienced during welding. This slower rate enabled precise observation of the moment when each sample reached the desired temperature and allowed safe manual extraction. A higher rate would have made this impossible to control.

Immediately after removal, the samples were cooled in a directed airflow created by two air blowers positioned 25 cm from the specimen.

After cooling, a portion of each specimen near the thermocouple hole was cut out and prepared for metallography and hardness measurement.

2.3 Metallography preparation and hardness measurement

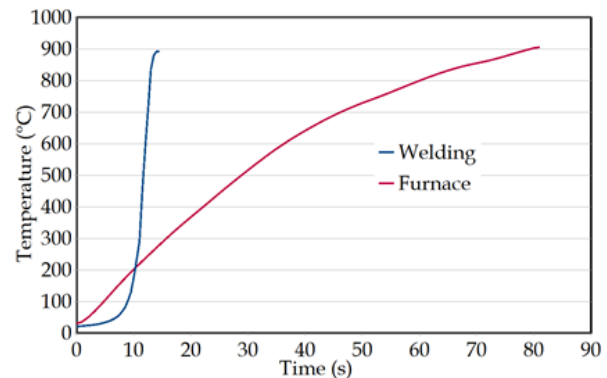
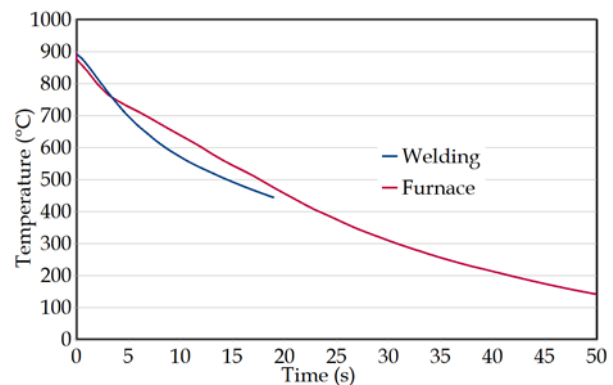
After cutting, a small piece from each treated sample was ground with silicon carbide papers of grit #220 and #500 and then polished using 3 µm diamond paste. Etching was performed in Nital-3 (3% nitric acid in ethanol) for 6 to 10 seconds to reveal the microstructure.

Vickers microhardness measurements were carried out on an Innovatest 400 instrument with a 0.5 kg applied load. Five indentations were made on each sample, and the dimensions of the resulting footprints were measured using ImageJ software.

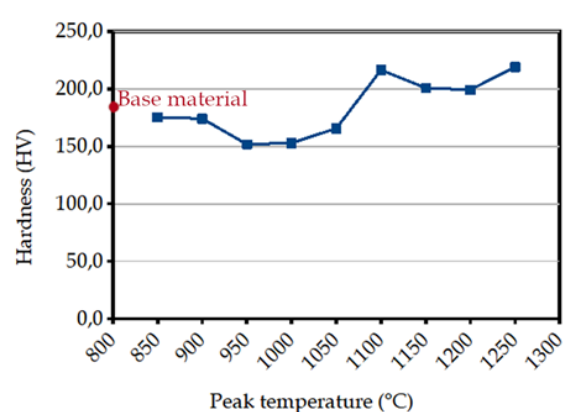
3. RESULTS

Fig. 1 presents a comparison between the heating curve obtained for a laboratory sample and the measured heating curve from an actual welding process. As previously discussed, the heating rate achieved within the furnace is substantially lower than that observed during real welding. However, achieving a realistic heating rate of over 150 °C/s, which occurs in real welding, is not feasible when the heating process must be stopped manually with precision. Although this represents a significant difference between the two heating processes [4], in practice it only implies that the microstructure obtained in the furnace corresponds to a location slightly closer to the fusion line than intended,

due to the higher overall heat input. In contrast, the cooling stage was reproduced far more reliably, as illustrated in Fig. 2, where the measured cooling rate closely matches that of the actual welding process.

**Fig. 1** Comparison of heating rates between actual welding and furnace heating**Fig. 2** Comparison of cooling rates in real welding and furnace conditions

The evolution of hardness as a function of peak temperature for S355 steel is shown in Fig. 3.

**Fig. 3** Hardness evolution as a function of peak temperature for S355 Steel

Given the inherently low carbon content of this steel, hardness values remain in the low range at all tested temperatures, as expected. A notable deviation from this

trend occurs at peak temperatures near 1100 °C. While lower peak temperatures cause slight softening, hardness rises sharply from approximately 160 HV to over 200 HV once the threshold temperature is exceeded. This behavior is characteristic of overheating, with significant grain coarsening and the appearance of Widmanstätten ferrite (Fig. 4) contributing to the increase in hardness.

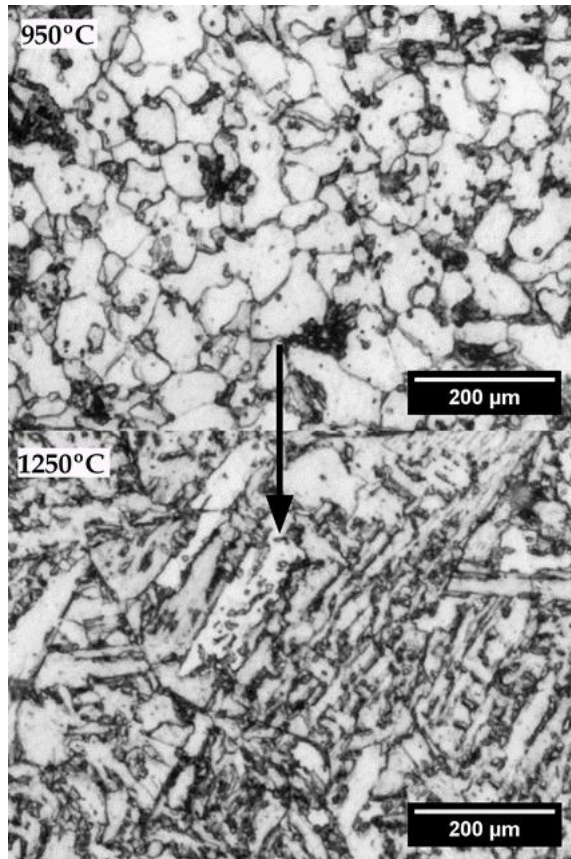


Fig. 4. Microstructure of S355 steel at low (950 °C) and high (1250 °C) austenitizing temperatures

The hardness of C45 steel (Fig. 5) exhibits a more pronounced increase beginning at a peak temperature of 1000 °C, corresponding to the formation of martensite once complete (or near-complete) austenization is achieved.

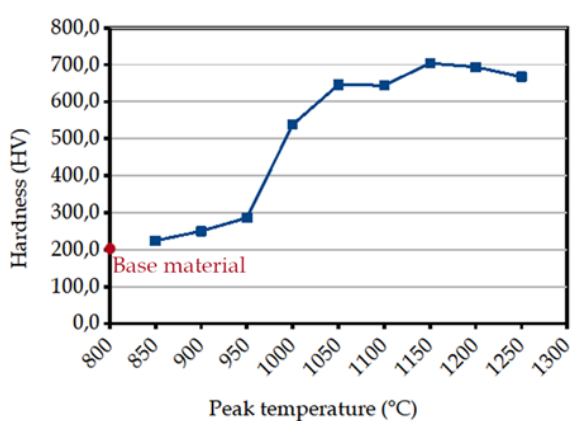


Fig. 5 Hardness evolution as a function of peak temperature for C45 Steel

This increase in hardness cannot be fully predicted by the steel's CCT diagram, which indicates predominantly fine pearlite and bainite for the applied cooling rate. However, it is somewhat expected, as higher peak temperatures shift the CCT curves to the right [8, 9], promoting greater austenization. This effect also appears to raise the martensite start temperature [6, 7], further favoring the development of harder microstructures.

The corresponding microstructural evolution is illustrated in Fig. 6. At 950 °C, small amounts of martensite are already present (white regions). As the peak temperature increases, the martensite fraction grows until the microstructure becomes almost entirely martensitic, with only a very minor presence of allotriomorphic and Widmanstätten ferrite, which is not visible in Fig.6.

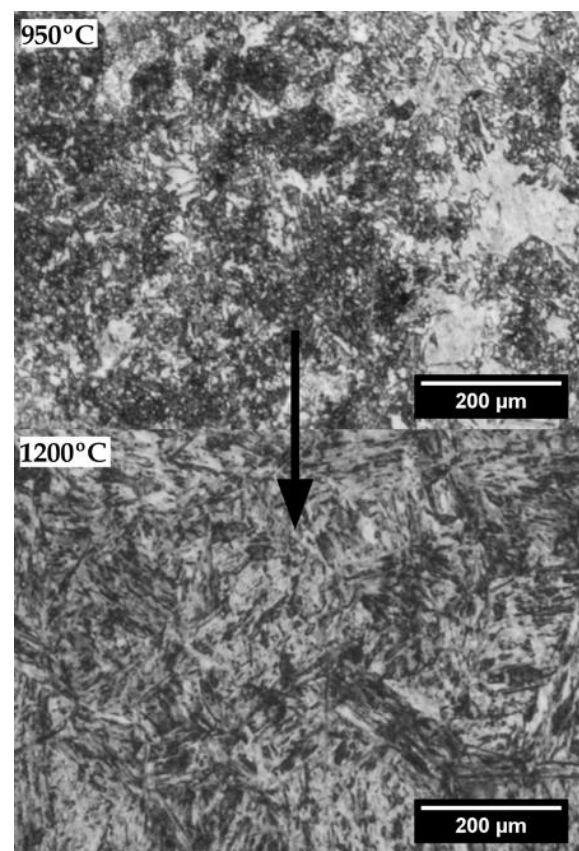


Fig. 6. Microstructure of S355 steel at low (950 °C) and high (1200 °C) austenitizing temperatures

Fig. 7 presents the hardness of S700MC steel samples. Since this steel derives its high mechanical properties from its fine-grained microstructure, the heat input during treatment promotes recrystallization and grain growth, resulting in a decrease in hardness in all tested samples compared to their initial state.

The graph (Fig.7) shows a gradual but consistent increase in hardness with rising peak temperature, without any abrupt change at a specific temperature. This trend is similar to that observed after one-hour annealings at different temperatures [10].

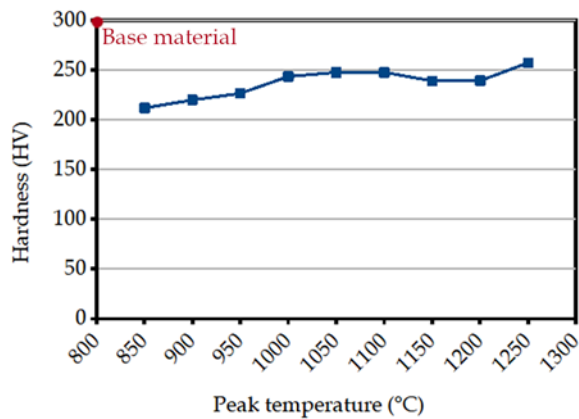


Fig. 7 Hardness evolution as a function of peak temperature for S700MC Steel

In contrast, a significant microstructural change is observed at a peak temperature of 1200 °C (Fig. 8). At this temperature, the microstructure transforms from fine equiaxed grains to coarser, irregular bainitic-ferritic grains exhibiting a Widmanstätten morphology

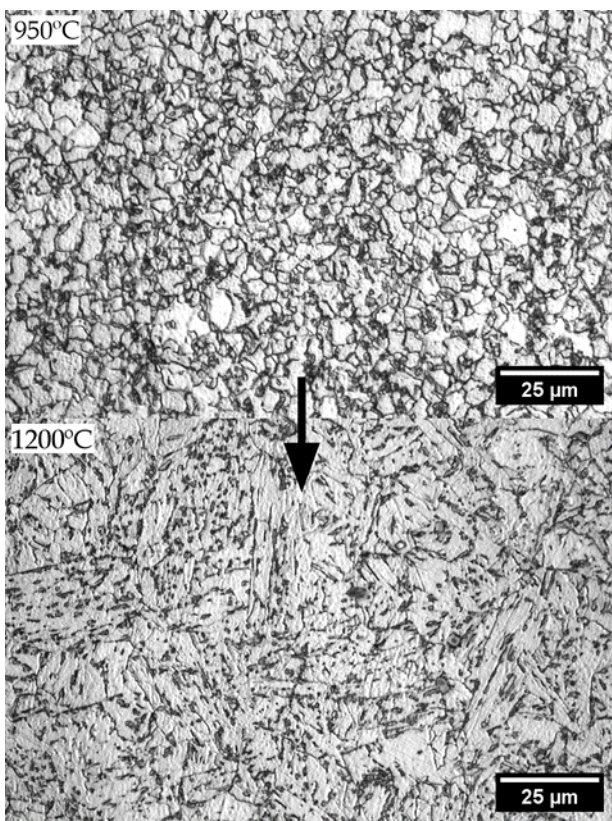


Fig. 8. Microstructure of S700MC steel at low (950 °C) and high (1200 °C) austenitizing temperatures

5. CONCLUSIONS

Understanding how peak temperature influences hardness in welded steels is crucial for assessing HAZ performance and preventing undesirable property variations in welded structures. In this study, the influence of peak temperature

on hardness was examined for three different steels, and the results reveal complex behavior that standard predictive approaches cannot fully capture.

All three tested steels exhibited an increase in hardness with rising peak temperature, a trend that cannot be predicted from their respective CCT diagrams. This emphasizes the challenges of accurately predicting the microstructure and mechanical properties of the HAZ in welded joints based solely on conventional heat-treatment data. In the two common carbon steels, S355 and C45, hardness shows a rapid increase once a critical threshold temperature is reached. This sharp transition is associated with significant grain growth and a change in the microstructural transformation during cooling: in S355, the microstructure evolves into Widmanstätten ferrite, while in C45, martensite is formed. In contrast, the HSLA structural steel S700MC exhibits a more gradual increase in hardness with peak temperature. Although no sudden jump in hardness is observed, the microstructure undergoes a pronounced change from fine to coarse grains between 1150 and 1200 °C, indicating the onset of overheating effects.

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NOTE

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