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EFFECT OF THE MAXIMUM TEMPERATURE ON THE HARDNESS AT THE HEAT AFFECTED ZONE OF THREE DIFFERENT CARBON STEELS AFTER A SLOW COOLING

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Abstract: *The welding of carbon steels causes microstructural changes at the heat affected zone that modify the behaviour of the material during its in-service life. Usually these changes are associated with an increase in the hardness and a loss of tenacity that, despite being within an acceptable range, should be considered and predicted when the weld is part of a highly demanding application. Unfortunately, the common Continuous Cooling Transformation (CCT) diagrams employed for heat treatments are not always a reliable data source as the heat cycle in welding is different from that of a quench, with higher temperatures and no soaking time. This implies that hardness at the heat affected zone (HAZ) will not depend only on the cooling rate but also on the heating rate and the maximum temperature at each point of the HAZ, parameters that control the transformation of perlite to austenite and the homogenization of austenite.*

This paper studies the effect of the maximum temperature at each point of the HAZ on the hardness of three different steels (S355, C45 and S700MC) when a relatively slow cooling rate is assured. This has been done by heating different samples inside a furnace till the selected maximum temperatures are reached and immediately cooling them under an air flow. The results show that once a certain temperature is reached, a transition from low to high hardness takes place. This transition is related to grain coarsening and the end of the austenization process, although, when compared to an oil quench, other changes like the apparition of Widmanstätten microstructures are also present.

Keywords: *Welding, steel, heat affected zone, hardening, overheating, CCT diagram, Widmanstätten.*

1. INTRODUCTION

In welding, the heat affected zone (HAZ) is the part of the base material that does not melt but whose microstructure changes as a result of being subjected to a thermal cycle. Each point of the HAZ, that surrounds the weld bead, experiments a different thermal cycle depending on the distance to the fusion line, where the material reaches the melting point. The closer to the fusion line, the higher the peak temperature reached by the material, the more intense the thermal cycle and, as a consequence, the greater the changes in the microstructure.

This gradual variation of the microstructure of the HAZ from the fusion line to the unaltered base metal is associated with a corresponding variation of properties. Actually, in carbon steels, those variations are not exactly gradual, as a quantitative leap is observed when the material reaches a temperature that leads to austenization. When this happens, and it's inevitable near the fusion line, the material can quench under a fast cooling and undesirable, very hard and fragile metallurgical phases can appear. The control of hardness at the HAZ is of paramount importance and one of the main control parameters that welding standards include, stablishing thresholds that must not be surpassed.

When necessary, a first prediction of the hardness a material can reach at the HAZ is possible taking into account the carbon content[1], using the equations like the Yurioka equation [2] or, still better, the common continuous cooling transformation (CCT) diagrams that take into account the cooling rate. Unfortunately, CCT diagrams are build for a thermal cycle where a low austenization temperature is reached and maintained for a certain period of time until complete austenization is achieved.

The welding thermal cycles differ from the ones associated with the CCT diagrams as there is no soaking time and higher temperatures are reached. The absence of a soaking time means time must be compensated with higher temperatures and that complete austenization is not achieved at the expected temperature[3],[4]. Furthermore, the total heat input to the material also depends on the heating rate. On the other hand, the high peak temperatures reached at some point of the HAZ imply a severe grain coarsening and a change in the behaviour of the material during cooling, including the possible apparition of Widmanstätten microstructures [5].

Although the effects the heating rate and peak temperature has been taken into account for multiple steels in [4], the data is only available for cooling rates over the critical one and, thus, not applicable to welding.

This lack of means to predict the exact nature of the microstructure at the HAZ after welding is usually not so important, but for high demanding applications, knowing the exact properties of the weld can be necessary. This is also important for finite elements simulations, as the mechanical behaviour of the material is not that of the original base metal.

This paper presents the results of a research designed to reproduce the thermal cycles at the HAZ at different distances to the fusion line on three different carbon steels to study the effect of the peak temperature on the hardness of the material.

2. MATERIALS AND METHODS

2.1. Materials

In order to study the influence of the peak temperature at different points of the HAZ on the hardness of welded carbon steels, three different steels were selected: S355, C45 and S700MC. All of them were available in plates of 3 mm thickness

S355 (EN 10025-2) is a mild structural steel commonly used in construction and engineering thanks to its good weldability and machinability. Due to its low carbon content, no hard structures are expected at the HAZ after welding under usual welding conditions. Its composition and mechanical properties can be seen in tables 1 and 2.

Table 1. Percentages (%) of main alloy elements for S355 steel

C	Si	Mn	Cu	C_{eq}
0.078	0.4	1.0	0.3	0.39

Table 2. Properties of the S355 steel plate

σ_u (MPa)	σ_Y (MPa)	A_L (%)	Hardness(HV)

560	452	29	180

C45 steel (EN 683-1) is a medium carbon steel usually selected for the manufacturing of shafts and other mechanical parts thanks to its good toughness, strength and wear resistance. C45 steel has a low weldability due to its high carbon content. So, preheating, an hydrogen back out treatment or a post-weld heat treatment is more than advisable. Its composition and mechanical properties can be seen in tables 3 and 4.

Table 3. Percentages (%) of main alloy elements for C45 steel

C	Si	Mn
0.478	0.24	0.79

Table 4. Properties of the C45 steel plate (as receibed)

σ_u (MPa)	σ_Y (MPa)	A_L (%)	Hardness(HV)
792	498	19.5	201

S700MC steel (EN 10149-2) is a structural high-strength low-alloy (HSLA) steel whose properties are mainly based on its small grain size thanks to a thermomechanical treatment. This steel has good weldability due to its low carbon content, but the heat input leads to a loss of properties at the HAZ due to grain coarsening. Tables 5 and 6 show its composition and mechanical properties.

Table 5. Percentages (%) of main alloy elements for S700MC steel

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

Table 6. Properties of the S700MC steel plate

σ_u (MPa)	σ_Y (MPa)	A_L (%)	Hardness (HV)
792	740	18.5	302

2.2. Samples preparation

For each steel, a pack of 10 mm width samples was cut from plates of 3 mm thickness. A hole of 0,9 mm diameter was drilled on each of the samples to insert the edge of a thermocouple.

These samples were heated to different peak temperatures, from 850 to 1250 °C, inside a furnace set at 50 °C over the peak temperature. The achieved heating rate was slower than the heating rate of the material during welding, but allowed the extraction of the samples from inside the furnace at the desired temperature. A higher heating rate would have been too fast to accurately determine the moment of extraction and manually remove the samples.

Once outside the furnace, the samples were inmediately cooled under air flow with the aid of two air blowers at a distance of 25 cm.

Once cold, a piece of the sample near the thermocouple hole was cut and prepared for metallography and hardness measurement.

2.3. Metallography preparation and hardness meaurement

After cut, a small piece of each treated samples was grinded using silicon carbide grinding paper, grit #220 and #500, and polished with 3 micron diamond paste. Subsequently, the samples where etched using Nital-3 (3% nitric acid in ethanol) during 6 to 10 seconds.

Hardness measurements were done using a load of 0.5 kg in a Innovatest 400 Vickers microhardness meter. 5 measurements were taken for each sample. The dimensions of the footprints were measured using the ImageJ software.

3. RESULTS

Figure 1 shows the heating curves of one sample compared with the measured heating curve of an actual welding process. As commented above, the heating rate inside the furnace was a lot lower, but it’s impossible to manually accurately stop the heating process with a heating rate over 150 °C/s, which is the real one.

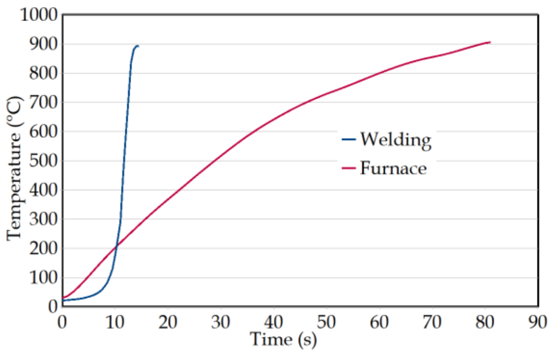

Figure 1. Heating rates in a real weld and inside a furnace

Although this represents an important difference between the two heating processes[4], in practice it only means the microstructure obtained at the furnace will correspond to a point slightly nearer to the fusion line than expected due to the greater heat input.

Regarding the cooling rate, figure **2** shows how it was more accurately reproduced.

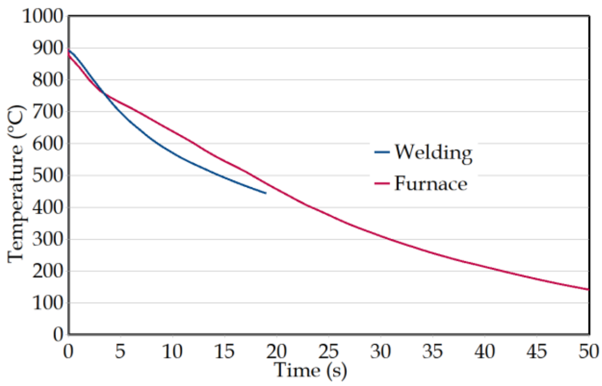

Figure 2. Cooling rates in a real weld and inside a furnace

The evolution of hardness with the peak temperature for S355 steel is presented in figure 3. As can be seen, hardness is always low regardless of the peak temperature, as expected due to the low carbon content of this steel.

Nevertheless, while for low peak temperatures there is a softening of the material when a peak temperature of 1100 °C is reached, hardness experiments a sudden increase from 160 to more than 200 HV. This change can be associated with the overheating of the sample, that leads to grain coarsening and the apparition of Widmanstätten ferrite, as can be seen in figure 4.

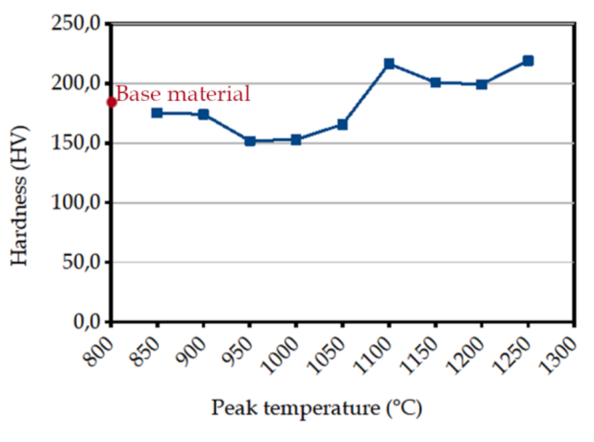

Figure 3. Relationship between hardness and peak temperature for S355 steel

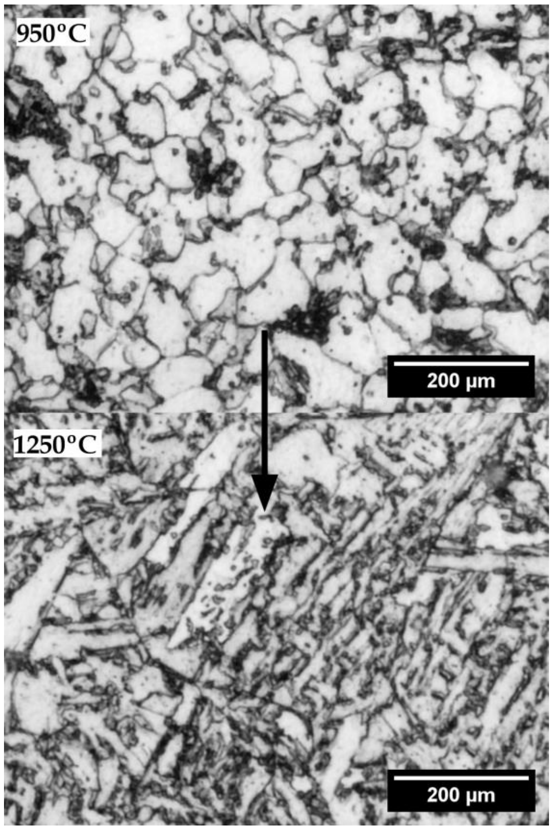

Figure 4. Microstructure of S355 steel when heated to low and high austenizing temperatures.

C45 steel hardness (figure **5**) shows a more marked transition that begins at a peak temperature of 1000 °C and is associated with the apparition of martensite once the complete (or almost) austenization is achieved.

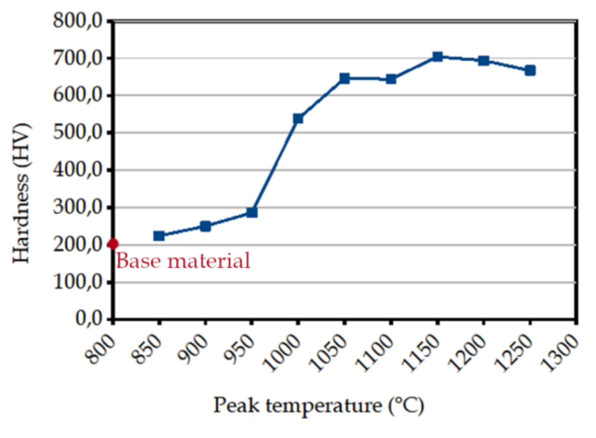

Figure 5. Relationship between hardness and peak temperature for C45 steel

This hardness increment can't be predicted by the CCT diagram of the steel, that predicts mainly fine pearlite and bainite for the used cooling rate, but is somehow expected because a higher peak temperature leads to a displacement of the CCT curves to the right [8], [9] and to a higher level of austenization. Also, this seems to shift the martensite start temperature to higher values [6], [7], all favouring harder microstructures.

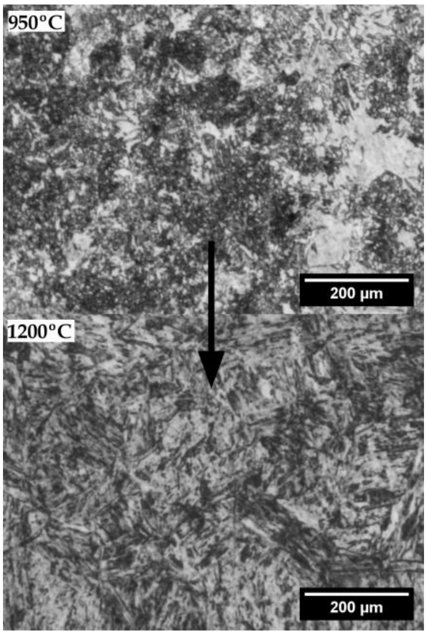

Figure 6. Microstructure of C45 steel when heated to low and high austenizing temperatures.

The change in the microstructure can be seen in figure 6. At 950 °C some martensite is present (white area). Its quantity rises as the peak temperature increases until all the microstruc ture is martensitic, except for a very small percentage of allotriomorphic and Widmanstätten ferrite not visible in the figure.

Figure 7 shows the hardness of the samples of the S700MC steel. As this steel obtains its high mechanical properties from its fine grain, the grain growth associated with the heat input leads to recrystallization, grain growth and a hardness decrease in all the tested samples with respect to the initial state of the samples.

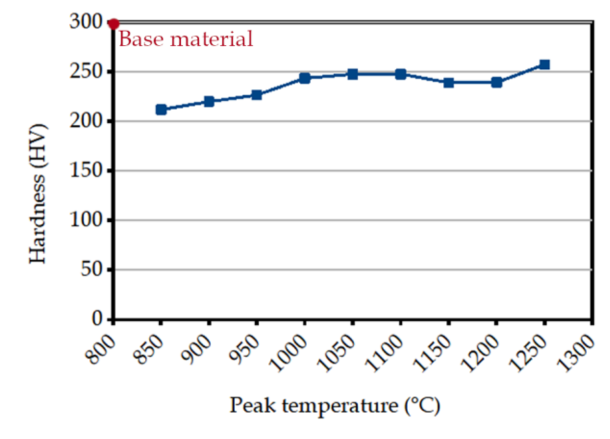

Figure 7. Relationship between hardness and peak temperature for S700MC steel

In this case the graph shows a slow but constant hardness increment as the peak temperature is increased, without a detectable abrupt leap at a concrete temperature. This evolution is similar to the one found after 1 hour annealings at different temperatures [10]. In contrast, there is a notable change in the microstructure (see figure **8**) when the peak temperature reaches 1200 °C. just at that temperature the microstructure changes from small equiaxial grains to more irregular bainitic-ferritic coarse grains with Widmanstätten shape.

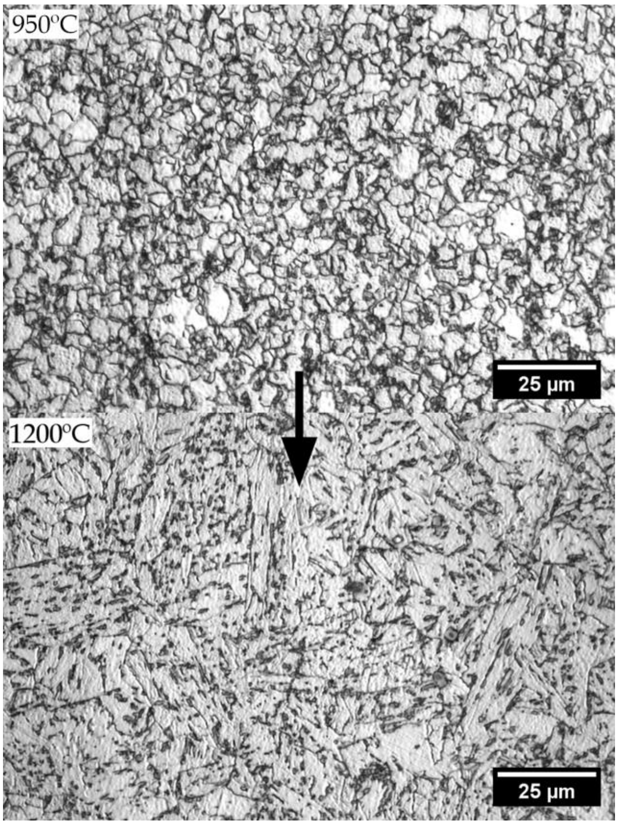

Figure 8. Microstructure of S700MC steel when heated to low and high austenizing temperatures.

4. CONCLUSION

All three tested steels have shown an increase in hardness as the peak temperature increases that is impossible to predict looking at the CCT diagrams of the steels. This confirms the difficulties of predicting the microstructure and properties of the HAZ in a welded joint with data from common heat treatments.

In the two common carbon steels, S355 and C45, hardness experiments a fast growth once a threshold temperature is reached. This transition is associated with grain growth and a change in the microstructure transformation during cooling to Widmanstätten ferrite in the first case and to martensite in the second.

The thermomechanical S700MC steel shows a small gradual rise in hardness with the peak temperature. Although in this case hardness does not experiment sudden leap, there is a sudden change from a fine to a coarse microstructure between 1150 and 1200 °C.

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