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Differences in Structural Transformations of Supercooled Austenite Exemplified in Selected CCT-W Diagrams (for Welding Conditions) and CCT Diagrams for Heat Treatment Conditions

Abstract: The article presents differences in the character of thermal cycle changes in welding conditions compared with the cycle of a traditional heat treatment, discusses the essence of austenite transformations in steels in welding conditions compared with heat treatment conditions, presents test results in the form of CTT-W diagrams (i.e. for welding conditions) for X10CrMoVNb9-1 (T/P91), X10CrWMoVNb9-2 (T/P92), X12CrCoWVNb12-2-2 (VM12-SHC), 7CrMoVTiB10-10 (P24), 10CrMo9-10 and S355JR grade structural steels and compares CTT-W diagrams with CCT diagrams for typical heat treatment conditions.

Keywords: austenite structural transformations, thermal cycle changes, heat treatment conditions

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Introduction

Structural transformations in solid-state steels during cooling are phenomena taking place in specific thermal conditions and, to put it simply, consist in the transformation of a component called austenite into other phases and structural components, e.g. ferrite, pearlite, bainite and martensite. Structural transformations not only change the microstructure of steels but also modify their mechanical and plastic properties.

Structural transformations of austenite, taking place in solid-state steels exposed to conditions of welding thermal cycles, are of crucial importance to the quality of welded structures made today. Designing modern steel structures and developing technologies for the welding of such structures require increasingly comprehensive and detailed knowledge about the properties of structural materials and of steel in particular. The usability of given steel results from its metallurgical, structural and technological weldability. Investigations of structural transformations constitute the basis of steel weldability tests.

The experience of Instytut Spawalnictwa, Gliwice, concerned with tests involving structural transformations in steels, is significant and demonstrated in a unique work (atlas) entitled “CCT-W Diagrams of Austenite Transformations” [1], written by researchers of Instytut Spawalnictwa, published in 1983 (Fig. 1) and being the only Polish publication of this kind. The appearance of new steels grades combined with increasingly high demands for welded joints entails the necessity of updating knowledge related to structural transformations in steels.

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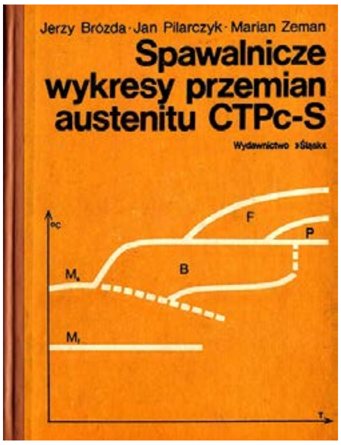

Fig. 1. Atlas of welding diagrams of austenite structural transformations prepared by research workers of Instytut Spawalnictwa in Gliwice [1]

Essence of Austenite Transformations in Steels in Welding Conditions in Comparison with Heat Treatment Conditions

One of the primary characteristics of steels indispensable for determining steel weldability for a given joining technique is the values of critical temperatures, i.e. the temperature at the beginning and at the end of structural transformations of austenite in solid-state steels during heating and cooling.

X10CrMoVNb9-1 (T/P91) – chemical element content in % by weight								
C	Mn	Si	P	S	Cr	Ni	Mo	Cu
0.10	0.34	0.24	0.014	0.002	8.35	0.14	0.907	0.16
Al	V	Nb	Ti	N	Co	W	B	-
0.012	0.215	0.074	0.004	0.066	0.024	0.002	0.0002	-

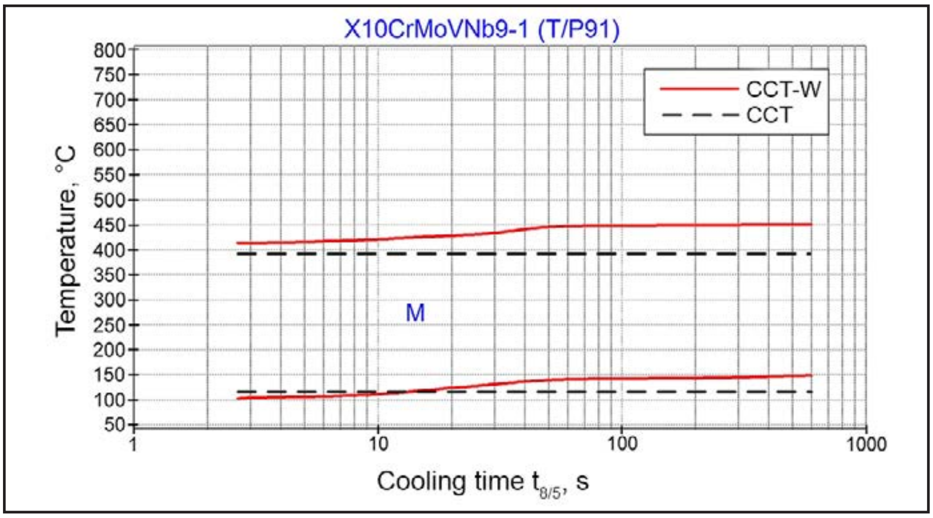

Fig. 2. Comparison of the CCT-W diagram [2] with the CCT diagram [3] for X10CrMoVNb9-1 (T/P91) steel

Welding conditions, due to the high dynamics and rate of heating and cooling processes as well as due to maximum temperature values, differ significantly from equilibrium conditions.

Quantitative data related to the dependence of types of phases, components of microstructure and steel properties on the temperature and time of austenite structural transformations are presented in diagrams designated as **TTT** diagrams, i.e. **T**ime – **T**emperature – **T**ransformation. Depending on the manner of cooling, TTT diagrams are divided into the following:

- TTT_i – for isothermal cooling,
- CCT – for continuous cooling.

In English language publications, diagrams for heat treatment conditions Time – Temperature – Transformation for continuous cooling are designated as **CCT** – **C**ontinuous **C**ooling **T**ransformation. Isothermal cooling is a cooling process where at a specific moment of a cooling phase, the value of temperature is stabilised (maintained) as long as it is necessary for steel being cooled to undergo structural transformations possible in given conditions.

CCT diagrams are mainly used when determining the microstructure and hardness of steel, e.g. during hardening, normalising or entire annealing. In addition, CCT diagrams enable the determination of a so-called critical rate V_k, i.e. the lowest possible cooling rate at which only the martensitic microstructure in steel is formed.

The specific character of welding conditions accompanying the heating and cooling of steel being welded is responsible for the fact that the course and character of a welding thermal cycle is significantly different from a traditional heat treatment cycle. The process of heat treatment is composed of three different stages, i.e. heating, holding (at a desired temperature) and cooling. All these stages are slow and stable in order to provide a workpiece with the greatest safety in terms of stresses, strains and cracks. Holding is aimed to equalise and stabilise the target treatment temperature in an entire workpiece.

The process of welding consists practically of two heat treatment stages, i.e. heating and cooling. In arc welding methods, thermal cycles are characterised by very high heating and cooling rates in the area of the Heat Affected Zone (HAZ). Near the welded joint fusion line, this rate can reach several hundred degrees Celsius per second. During welding, the obtainment of the maximum thermal cycle temperature is immediately followed by the cooling phase. Therefore, it can be stated that the holding stage is almost non-existent.

Another significant difference between the classical heat treatment and the welding process is the maximum temperature of a thermal cycle. For typical heat treatment operations affecting structural steels, i.e. annealing and hardening, maximum heating temperatures reach values within the range of approximately 650 to approximately 1000-1050°C. Even taking into consideration the solutioning procedure, the temperature of heat treatment does not exceed 1100-1150°C. In turn, during welding, in the HAZ, and particularly near the fusion line, temperatures easily reach approximately 1300 - 1400°C, or even the melting points of steels. For this reason, it must be assumed that during

X10CrWMoVNb9-2 (T/P92) – chemical element content in % by weight								
C	Mn	Si	P	S	Cr	Ni	Mo	Cu
0.10	0.48	0.21	0.016	0.005	8.96	0.13	0.36	0.11
Al	V	Nb	Ti	N	Co	W	B	-
0.018	0.18	0.047	0.003	0.0435	0.047	2.18	0.0022	-

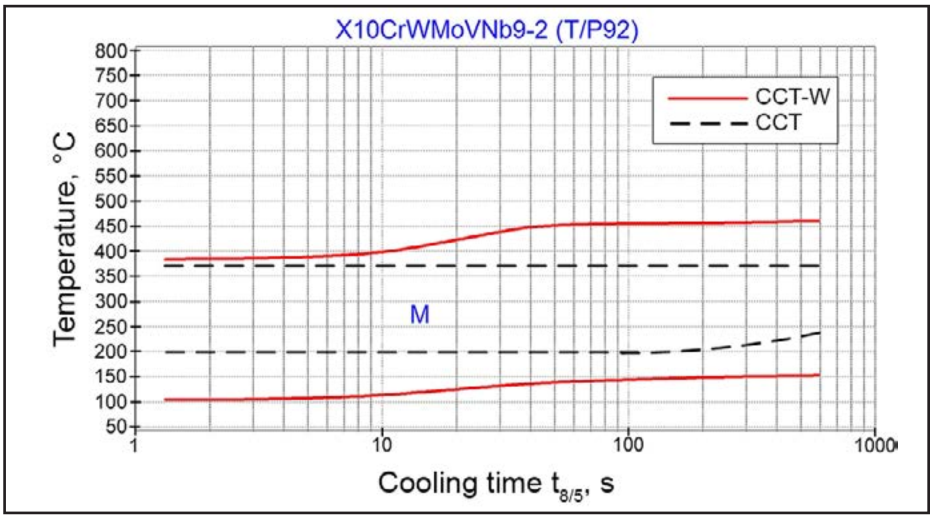

Fig. 3. Comparison of the CCT-W diagram [2] with the CCT diagram [3] for X10CrWMoVNb9-2 (T/P92) steel

X12CrCoWVNb12-2-2 (VM12-SHC) – chemical element content in % by weight								
C	Mn	Si	P	S	Cr	Ni	Mo	Cu
0.12	0.28	0.46	0.026	0.004	11.99	0.25	0.18	0.08
Al	V	Nb	Ti	N	Co	W	B	-
0.02	0.25	0.038	0.006	0.0465	1.54	1.69	0.0044	-

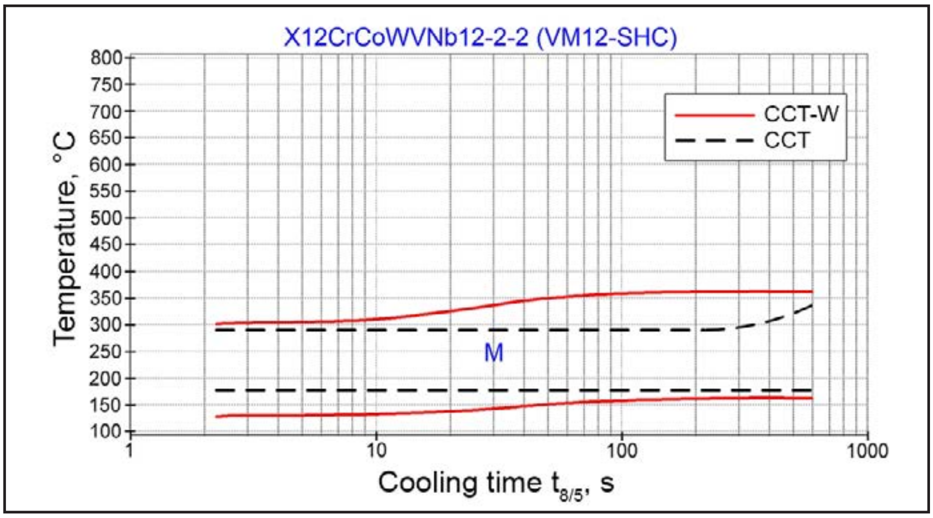

Fig. 4. Comparison of the CCT-W diagram [2] with the CCT diagram [3] for X12CrCoWVNb12-2-2 (VM12-SHC) steel

welding, maximum temperatures present in the joint HAZ areas are several hundred degrees Celsius higher than maximum temperatures reached during typical heat treatment operations.

7CrMoVTiB10-10 (T/P24) – chemical element content in % by weight								
C	Mn	Si	P	S	Cr	Ni	Mo	Cu
0,10	0,58	0,36	0,009	0,002	2,30	0,18	1,051	0,19
Al	V	Nb	Ti	N	Co	W	B	-
0,028	0,262	0,0068	0,081	0,0082	0,015	0,004	0,004	-

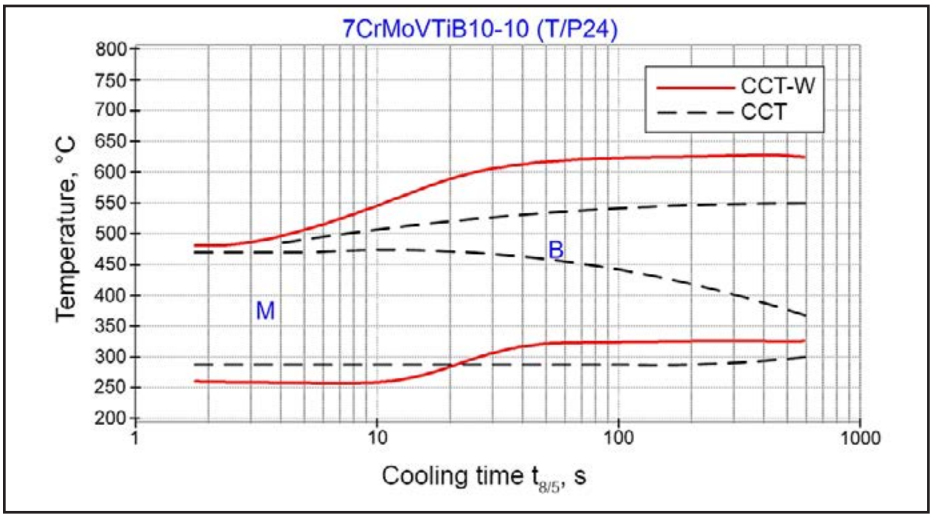

Fig. 5. Comparison of the CCT-W diagram [2] with the CCT diagram [4] for 7CrMoVTiB10-10 (T/P24) steel

10CrMo9-10 – chemical element content in % by weight								
C	Mn	Si	P	S	Cr	Ni	Mo	Cu
0.11	0.45	0.22	0.007	0.003	2.02	0.09	0.96	0.10
Al	V	Nb	Ti	N	Co	W	B	-
0.018	0.007	0.0014	0.003	0.0094	0.014	0.004	0.0002	-

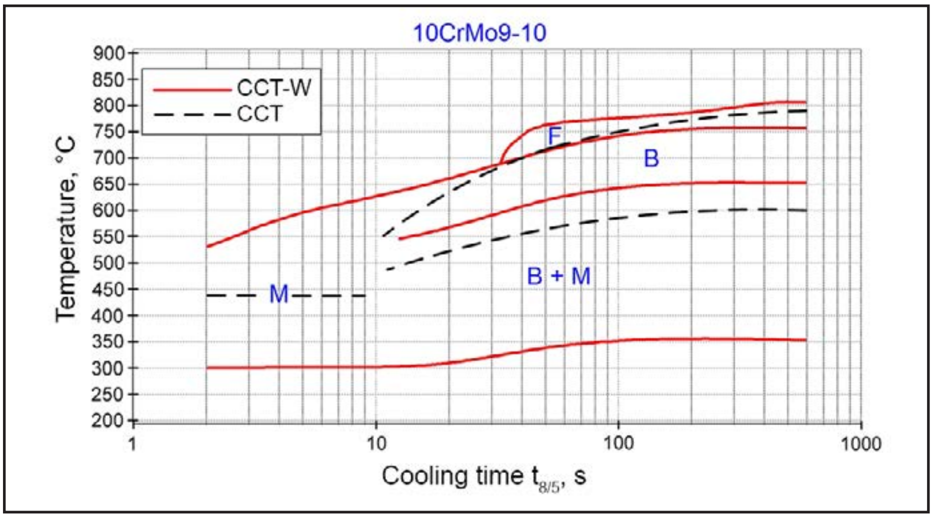

Fig. 6. Comparison of the CCT-W diagram [2] with the CCT diagram [5] for 10CrMo9-10 steel

It should be noted that multilayer welding is accompanied by overlapping and interaction of two or more thermal cycles. As a result, partially melted zones of the welded joint HAZ areas can undergo cyclically repeated structural transformations depending on how many times the temperature A_{C3} has been exceeded.

Due to the differences described above, austenite structural transformations during the welding of steel are presented in diagrams Time – Temperature – Transformation with Continuous Cooling for Welding conditions designated as **CCT-W**. CCT-W diagrams are an important source of information about the effect of welding thermal cycles on the microstructure and properties of welded steels and, for this reason, are useful when developing welding technologies.

Welding thermal cycle parameters, i.e. maximum temperature T_{max} and cooling time $t_{8/5}$, affect the microstructure of steel welded. Cooling time $t_{8/5}$ represents the cooling time of the HAZ area of a welded joint within the temperature range of 800 to 500°C. CCT-W diagrams are constructed after determining initial and final temperature values (critical temperatures) of individual solid-state austenite structural transformations. In turn, values of critical temperatures are determined on the basis of the testing methodology used, i.e. on the basis of measurements of three quantities characterising physical phenomena taking place in steel subjected to welding during its heating and cooling, i.e. thermal expansion, changes of magnetic properties (transition from the ferromagnetic state into the paramagnetic state) and temperature in the function of time.

Comparison of CCT-W Diagrams with CCT Diagrams for Selected Structural Steels

The comparison of Cct-w diagrams with Cct diagrams involved the use of several exemplary structural steels intended for operation at higher temperatures, i.e. steels used in the power industry:

– X10CrMoVNb9-1 (T/P91), X10Cr-WMo-VNb9-2 (T/P92) and X12Cr-CoWVNb12-2-2 (VM12-SHC) grade steels of martensitic microstructure,
– 7CrMoVTiB10-10 (T/P24) grade steel of bainitic microstructure,
– 10CrMo9-10 grade steel (equivalent to 10H2M grade Polish steel) of ferritic martensitic microstructure and S355JR grade steel of ferritic-pearlitic structure; the latter steel is often used when making various welded structures.

Comparisons of diagrams of austenite structural transformations in steels in welding conditions (Cct-w) with Cct diagrams for heat treatment conditions are presented in Figures 2-7; symbols used in the diagrams: M – martensite, B – bainite, F – ferrite and P – pearlite.

The Ctt diagrams and the Ctt diagrams for welding conditions presented in Figures 2-7 reveal a significant resemblance as regards the general character of the curves and structural areas present in the diagrams. In turn, visible differences are connected with positions of the curves in relation to the temperature axis.

S355JR – chemical element content in % by weight								
C	Mn	Si	P	S	Cr	Ni	Mo	Cu
0.15	1.39	0.33	0.008	0.012	0.04	0.09	0.03	0.15
Al	V	Nb	Ti	N	Co	W	B	-
0.031	0.002	0.001	0.004	0.01	0.01	0.004	0.0005	-

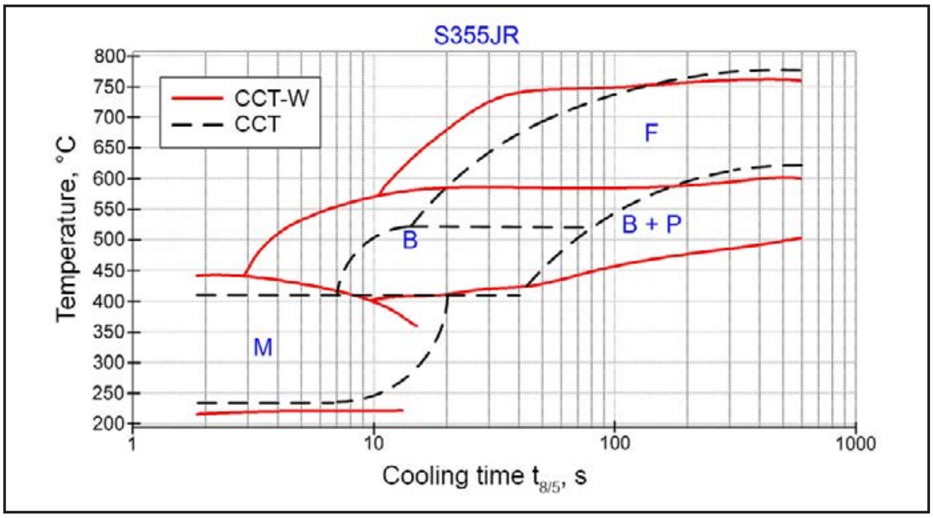

Fig. 7. Comparison of the CCT-W diagram [2] with the CCT diagram [6] for S355JR steel

Generally, in welding conditions, structural transformations of austenite in solid-state steels take place in wider temperature ranges, i.e. starting at a higher temperature and ending at a lower temperature, if compared with heat treatment conditions. The differences are primarily ascribed to various values of steel austenitisation temperatures (higher temperatures for welding conditions), various values of austenitisation times (for welding conditions this time is less than one second, whereas for heat treatment conditions this time exceeds ten minutes), various cooling times, various steel cooling conditions as well as various chemical compositions (within a given steel grade), for which the compared transformation diagrams were made.

Summary

Due to the differences in the CTT diagrams and the CTT diagrams for welding conditions presented in the previous section, when designing a welding technology, and particularly when defining the preheating temperature of joints before welding, as well as when defining post-weld heat treatment parameters, it is recommended to use information resulting from CTT diagrams for welding conditions. It is particularly important when welding structural steels of limited weldability. The effective use of CTT diagrams for welding conditions when designing welded structures and welding technologies makes it possible to avoid technological errors and limit the risk of crack formation in structures containing welded joints.

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