

**INTRODUCTION**

Simulation of thermal cycle of base metal individual point is a laboratory method suitable for weldability investigations. Simulations of thermal cycle of base metal individual point are followed by investigations on specimens, e.g. hardness and toughness testing, tensile test and investigations of micro structure. This method is suitable for investigations in different production processes, in which thermal cycle at heating and/or cooling has significant influence on product quality. However, the most important application of this method is in investigations of base metal weldability at single pass and multi pass welding. Depending of requirements for weldability investigations, it is possible to perform single-cycle or multi-cycle weld thermal cycle simulation and appropriate mechanical testing or other investigations. It gives relatively fast information, which can accelerate process of obtaining WPAR/PQR (Welding Procedure Approval Record / Procedure Qualification Record) and reduce costs of production (e.g. investigations at PQR/WPAR, PWHT).

**THERMAL CYCLE SIMULATION METHOD**

Thermal cycle simulation method is an experimental method developed mostly for weldability investigations. There are several laboratory devices for thermal cycle simulation (Smitweld, Gleeble, Thermorestor). Figuration and dimensions of probe for thermal cycle, detail of setting the probe in simulation device, and scheme of execution unit for simulation of thermal cycle are given below. Thermo couple setting by capacitor discharging method on each specimen followed after preparing specimens for thermal simulation (Figure 1). Specimen was inserted in jaw of block for fixation (position 6 in Figure 4) and stationary sensor was set for dilatation measurement (position 4 in Figure 5).

![Figure 1 Dimensions of thermal cycle specimens according to Smitweld TCS 1406 method, in the case of indirect cooling (a) and in the case of indirect and additional direct cooling by water (b). [1]](image1)

![Figure 2 Dimensions of thermal cycle specimens according to the Thermorestor-W method](image2)

![Figure 3 Specimen for thermal cycle simulation by the Gleeble method](image3)
Application of Weld Thermal Cycle Simulator in Manufacturing Engineering

Figure 4 Execution unit on simulator of thermal cycle type Smitweld CTS 1405. [1] where 1- Base screw with bolt, 2 - Pipe connectors for indirect cooling, 3 - Water flow canal for indirect cooling, 4 - Dilatometer porter and temperature sensor, 5 - Base screw for jaws, 6 - Jaw block for fixation, 7 - Contraction screw for direct cooling application, 8 - Pipe connectors for direct cooling, 9 - Direct cooling block, 10 - Current cable

Figure 5 Position of dilatometer, thermocouple and gas protection. [1], where: 1 - Probe, 2 -Thermocouple, 3 - Station dilatometer sensor, 4 - Movable dilatometer sensor, 5 - Micrometer screw for dilatometer regulation, 6 - Gas protection unit

Sometimes there is a need for gas shielding during simulation (e.g. during precise dilatation measuring and very sensitive materials on air influence on elevated temperatures), in the case of which the gas protection unit is set (position 6 in Figure 5). After connecting all sensors (for temperature and dilatation), very rapid heating and cooling follows in controlled conditions (determined start temperature, heating and cooling rate, peak temperature, cooling time between 800 and 500 °C). The thermal simulation process is monitored by a computer and all data are available after simulation for further processing and application. In this way, controlled heat input in base material is applied and it is possible to expect very similar effect during real welding in workshop in case of controlled welding parameters (heat input achieved by means of welding current and voltage and welding speed). Figure 6a shows Smitweld TCS 1406 before thermal cycle simulation and Figure 6b during rapid heating by electric resistance system. After thermal simulation, specimens were prepared for next investigation (e.g. hardness measurement, toughness testing, metallography investigations).

Figure 6 Detail of simulation of test probe on simulator of thermal cycle type Smitweld CTS 1405 (a - specimen before and after thermal simulation, b - specimen during thermal cycle simulation)

Weld thermal simulation can be performed as single cycle or multi cycle. Figure 7a shows an example of single weld thermal cycle simulation and Figure 7b shows double weld thermal cycle simulation. Besides temperature–time relationship during heating and cooling, it is possible to monitor the temperature–dilatation relationship, which is very important in materials science.

Figure 7a Single weld thermal cycle simulation; temperature-time and temperature-dilatation relationship. [2]
The heat input and cooling conditions have crucial influence on microstructure and mechanical properties of base material and welded joint. There are many mathematical solutions derived from Fouriers differential equation for heat conduction, which determine relationship between welding parameters, physical and geometric variables on the one side, and cooling time (cooling rate) on the other side. For the selected heat input, it is possible to calculate border thickness between 2 and 3-dimensional heat flows at arc fusion welding (equation 1). If the border thickness (Ingr calculated thickness) is over real thickness at construction, 2-dimensional heat flow model has to be used (high speed moving line energy source at thin plate). Otherwise, 3-dimensional model will be used (high speed point energy source on very thick plate). [3-6]

\[
\delta_{\theta} = \sqrt{\frac{q}{2 \cdot \rho \cdot c} \left( \frac{1}{500-T_0} + \frac{1}{800-T_0} \right)} \quad [mm] \tag{1}
\]

In case of 2-dimensional heat flow, the heat input can be determined by equation 2 and 3. [3-6]

\[
E_{ef} = \frac{q}{\nu} \cdot \frac{U \cdot \eta}{\nu} = \sqrt{\frac{4 \cdot \pi \cdot \lambda \cdot \rho \cdot c \cdot t_{8/5} \cdot \delta^2}{\left( \frac{1}{500-T_0} \right)^2 - \left( \frac{1}{800-T_0} \right)^2}} \quad [J/mm] \tag{2}
\]

\[
t_{8/5} = \frac{E_{ef}^2}{4 \cdot \pi \cdot \lambda \cdot \rho \cdot c \cdot \delta^2} \left[ \left( \frac{1}{500-T_0} \right)^2 - \left( \frac{1}{800-T_0} \right)^2 \right] \quad [s] \tag{3}
\]

In case of 3-dimensional heat flow, the heat input can be determined by equation 4 and 5. [3-6]

\[
E_{ef} = \frac{q}{\nu} \cdot \frac{U \cdot \eta}{\nu} = \frac{2 \cdot \pi \cdot \lambda \cdot t_{8/5}}{500-T_0} \quad [J/mm] \tag{4}
\]

\[
t_{8/5} = \frac{E_{ef}}{2 \cdot \pi \cdot \lambda} \left( \frac{1}{500-T_0} - \frac{1}{800-T_0} \right) \quad [s] \tag{5}
\]

Based on Fouriers differential equation, the cooling rate is derived at determined temperature for 2- and 3-dimensional heat flow model. [3-6] Cooling rate (w) at temperature T for 2-dimensional heat flow model:

\[
w = \frac{dT}{dt} = -\frac{2 \cdot \pi \cdot \lambda \cdot c \cdot \rho}{E_{ef}} \cdot \frac{(T-T_0)^3}{\delta^2}, \quad ^{oC/s} \tag{6}
\]

Cooling rate (w) at temperature T for 3-dimensional heat flow model:

\[
w = \frac{dT}{dt} = -\frac{2 \cdot \pi \cdot \lambda \cdot (T-T_0)^2}{E_{ef}}, \quad ^{oC/s} \tag{7}
\]

Therefore, in that case it is possible to compare cooling time and mechanical properties and microstructure after base metal exposure to thermal cycle simulator under controlled conditions. An example of that influence is evident in Figure 8, showing TTT (Temperature-Time-Transformation) diagram for 10CrMo910 steel, which is very often used in steam boiler components production. This type of investigation is very expensive and time-consuming, but it is very valuable for modern materials during weldability investigations and preparation of welding process qualification documents. It is also possible to improve quality of existing documents, if these data are available to welding engineers. In that case, the reliability of weldments will be improved, and the weld thermal cycle simulation is cost effective. At some welding products with increased risk of failure (power plants, LPG and LNG tanks), contribution to quality and reliability can significantly reduce the failure risk.

**Figure 8** Influence of cooling time on mechanical properties of 10CrMo910 steel after austenitisation and cooling at different cooling time. [7]

**INVESTIGATION ON SPECIMENS AFTER WELD THERMAL CYCLE SIMULATION IN HAZ**

HAZ region in welded joint is narrow and materials in the HAZ are heterogeneous. Many different microstructures arise in HAZ under the influence of weld thermal cycle. This paper

http://dx.doi.org/10.12776/mie.v12i1-2.177
analyses fine grain HAZ of T/P91 steel, as this HAZ region is the most problematic due to creep in practical application. After weld thermal cycle simulation of P91 steel (Figure 9), martensite start and martensite finish temperature are determined after heating and cooling under controlled conditions, within the regime shown on Figure 10a. The following input data were used for weld thermal cycle simulation (Figure 10a): Preheating temperature: $T_0 = 200 \, ^\circ\text{C}$, Heating speed: $150\, ^\circ\text{C}/\text{s}$, Maximal temperature: $T_{\text{max}} = 975\, ^\circ\text{C}$, Holding time on maximal temperature: 0.5 s, Cooling time between 800 and 500 °C: $t_{8/5} = 20$ s, Duration of the simulation: $t_{\text{finish}} = 300$ s.

Influence of weld thermal cycle and dilatation curve is shown in Figure 10b. Start of transformation of austenite into martensite ($M_s$) is 405 °C and finish ($M_f$) is 325°C.

After welding of T/P91 steel, it was necessary to perform PWHT at 750 – 770°C (Figure 11), while investigating the influence of PWHT at that temperature. Figure 12 shows microstructure of base material and Figure 13 shows microstructure of fine grain HAZ before PWHT (a), after PWHT (b).
start and martensite finish temperature for fine grade zone in HAZ and investigation of influence PWHT in fine grade HAZ of modern steam boiler steel T/P 91 are determined as an example of application of weld thermal cycle method. The results confirm strong influence of PWHT on hardness.

REFERENCES


LIST OF USED SYMBOLS

\( T \) – preheating temperature [\(^{\circ}\)C]
\( \delta \) – thickness [mm]
\( \lambda \) – thermal conductivity [W/(mm\(^{\circ}\)C)]
\( c \) – specific thermal capacity [J/(kg\(^{\circ}\)K)]
\( t \) – time [s]
\( v \) – welding speed, [mm/s]
\( q \) – heat flow \([q=U\cdot I \cdot \eta_l], [W]\)
\( \eta_l \) – arc weld efficiency [-]