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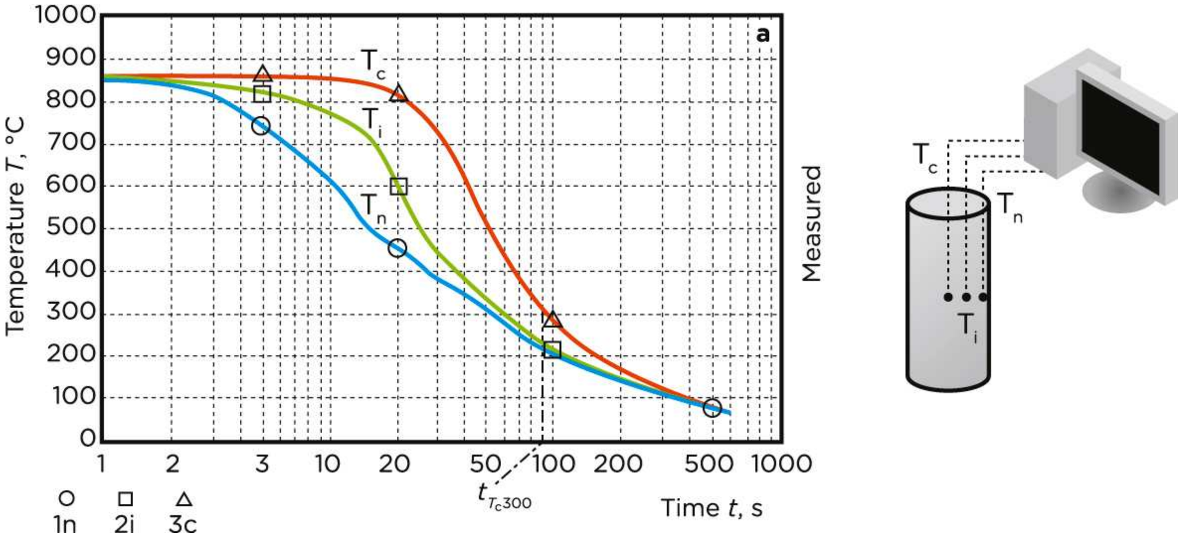
TEMPERATURE GRADIENT QUENCHING ANALYSIS SYSTEM

When hardening real engineering components, modern quenching technology uses different quenchants (different kinds of oils, different polymer solutions and other water-based solutions, molten salt-baths, fluidized beds, and fast moving compressed gases).
The workshop conditions at quenching, widely differ from those in laboratory tests. In each practical case the quenching parameters i.e. the bath temperature and the fluid agitation rate, as well as its flow direction, are different. There are also different quenching techniques:
Direct immersion quenching; Intensive quenching; Interrupted quenching; Delayed quenching, Martempering; Austempering; Spray-quenching.
Nowadays, there is no a method that would enable a real comparison among different quenchants, quenching conditions and quenching techniques, in relation to the achievable depth of hardening, thermal stresses, and the risk of crack formation.
The main criterion for such a comparison is the *quenching intensity* during the whole quenching process, i.e. the ability to extract heat from the heated workpieces (dynamic of heat extraction). This implies that the quenching intensity cannot be designated by a sole number (as is the case with the Grossmann's „H“), neither can it be measured and recorded by a small specimen used in laboratory tests.
The physically most correct way to measure and record the heat extraction dynamics at quenching is the heat flux density [W/m^2] on the surface of the quenched object. To compare this value for all quenchants and quenching conditions, one needs a relevant probe. Such a probe, (when cylindrical, workpieces are involved), is the Liscic/Nanmac probe having 50 mm diameter and 200 mm length. It is made of austenitic stainless steel AISI 304, and is instrumented with 3 thermocouples on the same radius at half length of the probe. The outer thermocouple is of special design (U.S. Pat. No. 2,829.185) which measures the temperature at the very surface; the intermediate thermocouple measures the temperature at 1.5 mm below the surface, and the third one measures the temperature at the centre of the probe's cross-section.

Specific features of the Liscic/Nanmac probe are:

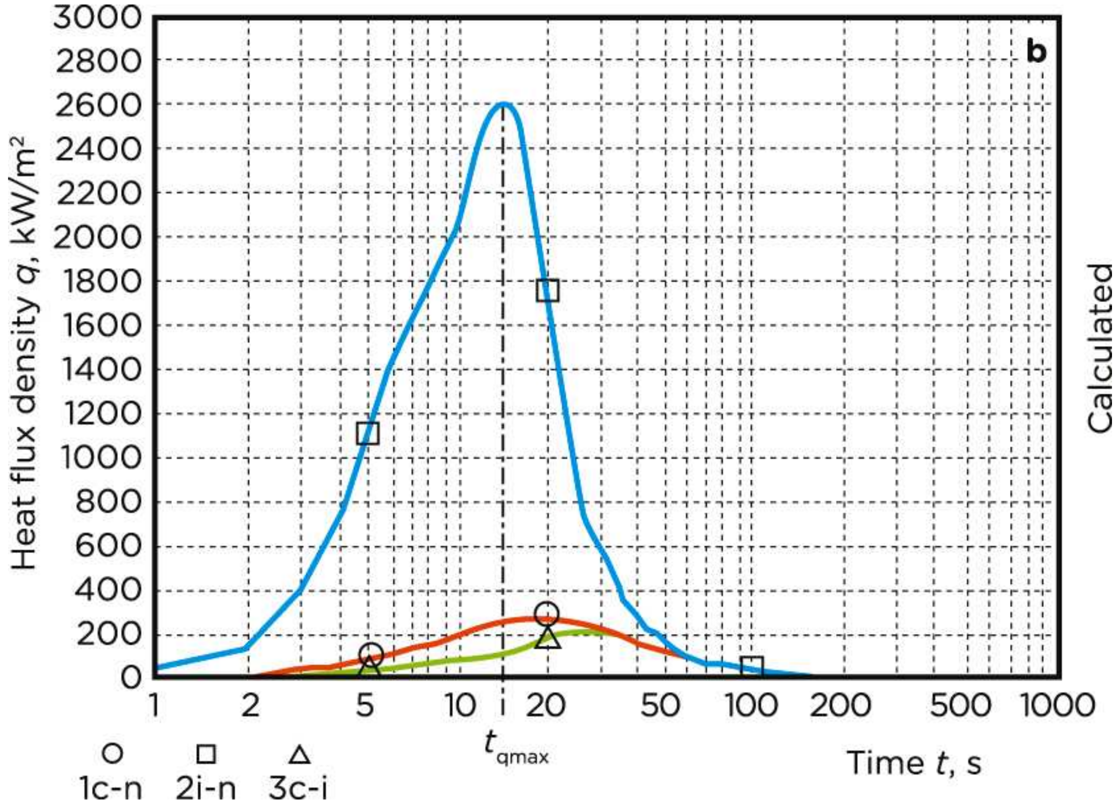
- Its surface thermocouple has extremely short response time (10^{-5} seconds), which records the smallest, and fastest temperature change on the surface in real time.
- The surface condition of the probe is maintained constant by polishing the thermocouple sensing tip before each measurement (self renewable thermocouple).
- The body of the probe, made of an austenitic stainless steel, does not change in structure during heating and cooling, i.e. it does not evolve or absorb heat because of phase transformation.
- The mass of the probe and its heat capacity is great enough to secure (using the length to diameter ratio of 4) a one dimensional radially symmetric heat flow at the half length cross-section, where the thermocouples are located.
- The diameter of the probe (50 mm) is enough big to minimize the dependence of the heat transfer coefficient on the diameter. Such a dependence is greater for smaller bar diameters.

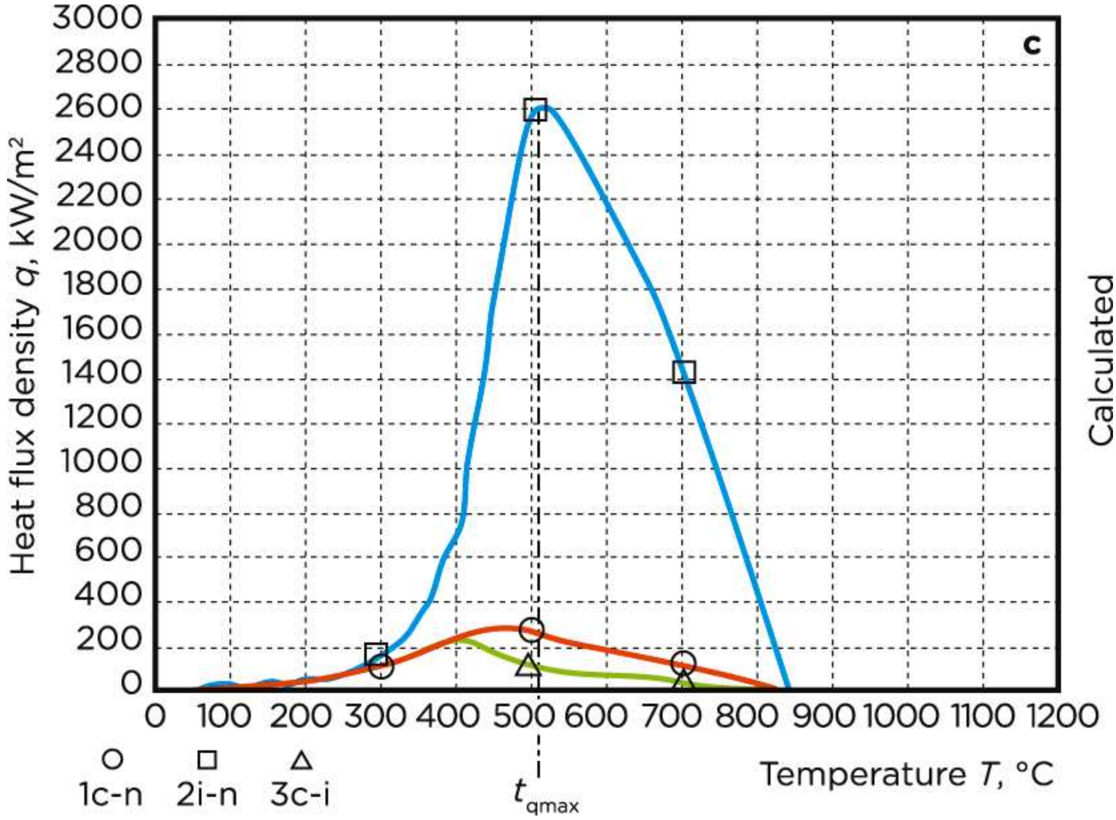
At each test the Liscic/Nanmac probe is heated through to 850 °C and immersed vertically in the quenchant. Three cooling curves: T_n at the very surface, T_i at 1.5 mm below the surface, and T_c in the centre of the cross-section are recorded, as shown in Fig. a.

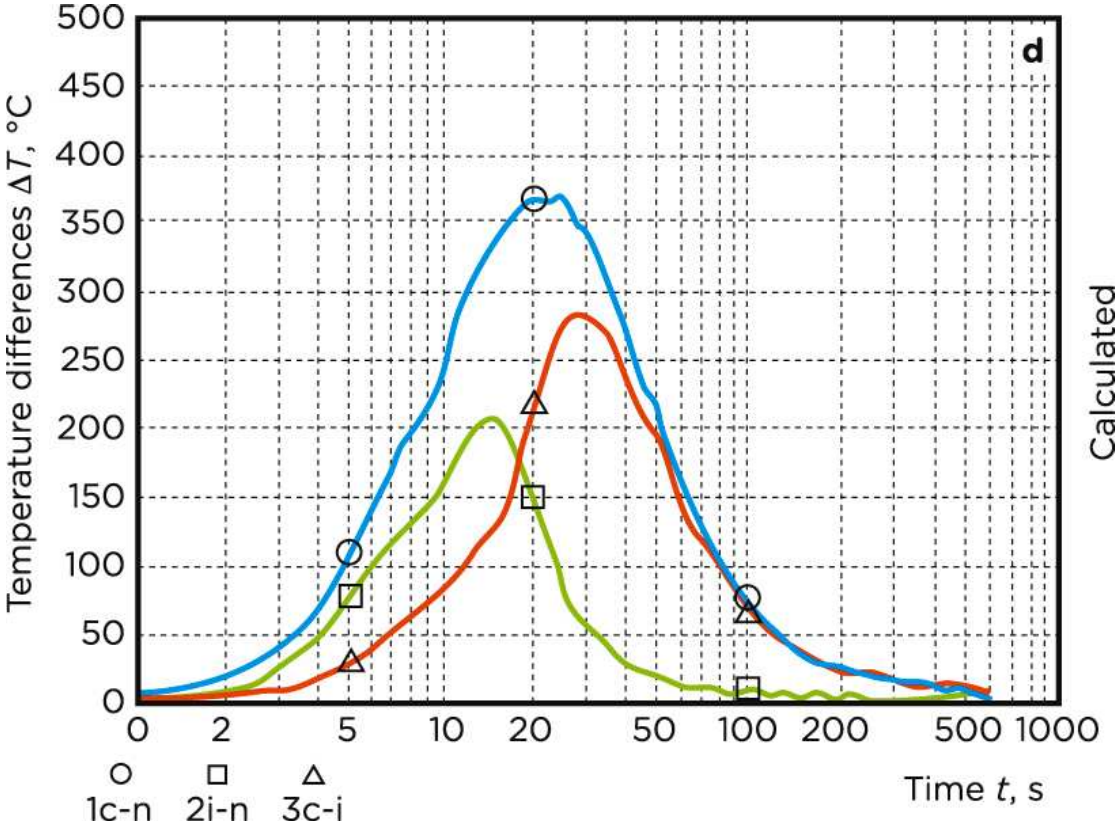


From these recorded cooling curves the following thermodynamic functions are calculated:

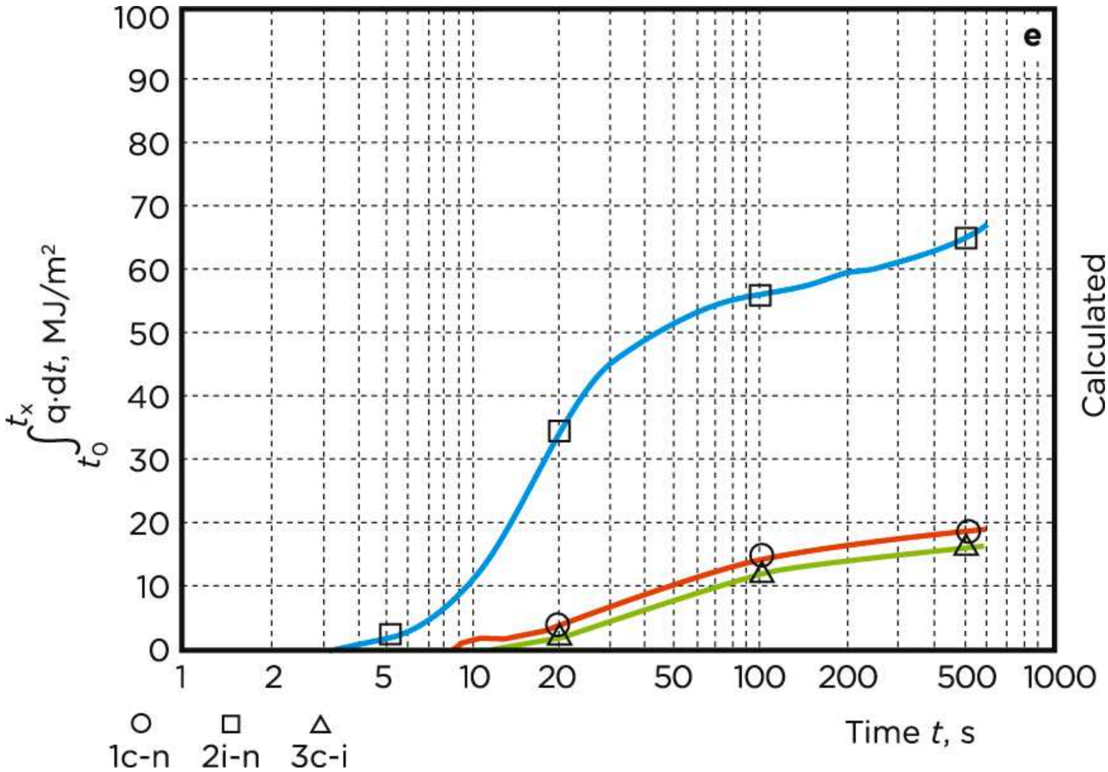
- Heat flux density - **q** [W/m^2] as function of time, see Fig. b.
- Heat flux density **q** [W/m^2] as function of surface temperature, see Fig. c.
- Temperature difference - **ΔT** = f (t) between all points in which thermocouples are located, as function of time, see Fig. d.
- Integral below the heat flux density curve - **∫qdt** [MJ/m^2] representing the heat extracted as function of time, see Fig. e.
- Cooling rates - **δT/δt** [K/s] as function of temperature, in all points where thermocouples are located, see Fig. f.


b
Heat flux density q, kW/m²
3000
2800
2600
2400
2200
2000
1800
1600
1400
1200
1000
800
600
400
200
0
1
2
5
10
20
50
100
200
500
1000
t qmax
Time t, s
Calculated
1c-n
2i-n
3c-i

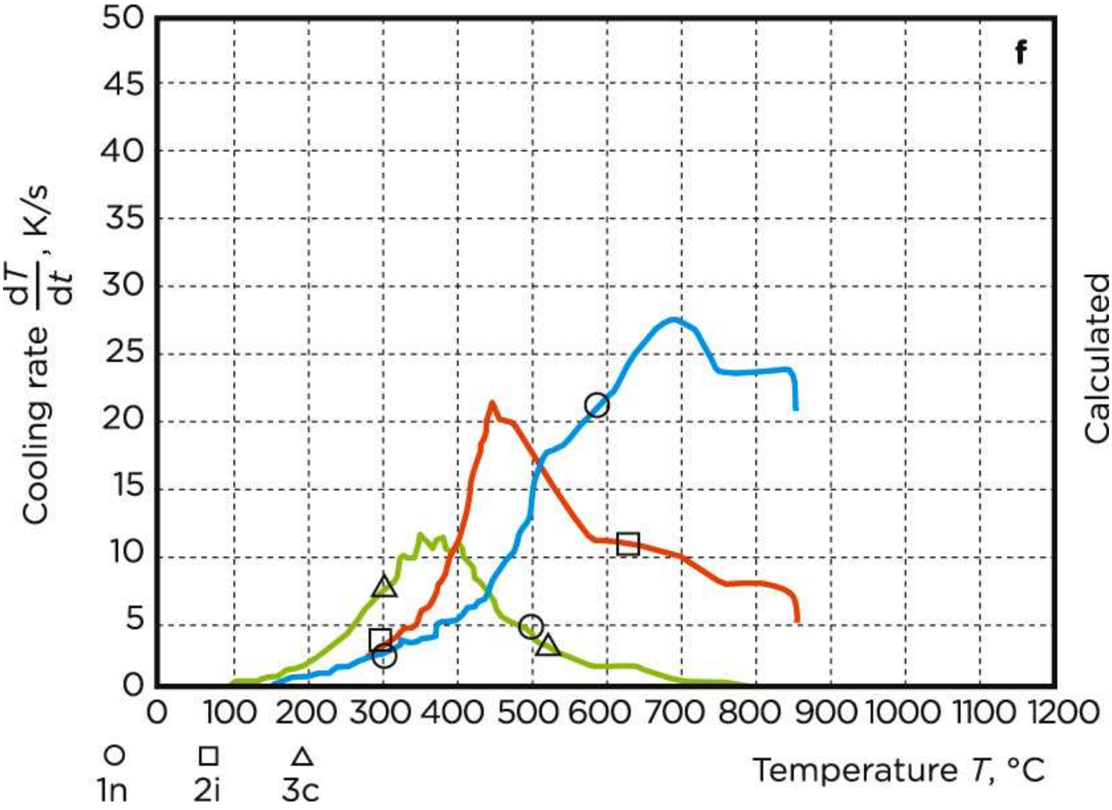

c
Heat flux density q, kW/m²
3000
2800
2600
2400
2200
2000
1800
1600
1400
1200
1000
800
600
400
200
0
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
Temperature T, °C
t qmax
Calculated
1c-n
2i-n
3c-i



Temperature differences ΔT, °C
d
Calculated
Time t, s
1c-n
2i-n
3c-i



$\int_{t_0}^{t_x} q \cdot dt$, MJ/m²
e
Calculated
Time t, s
1c-n
2i-n
3c-i



The shown diagrams belong to the case when the Liscic/Nanmac probe was quenched in a mineral oil of 20 □C, without agitation.

In order to define and evaluate the quenching intensity in the workshop practice from the calculated thermodynamic functions, the following four criteria are used:

1. The maximum heat flux density, Fig. b - q_{max} [MW/m^2]
2. The time from immersion when the maximum heat flux density occurs - t_{qmax} [s]
3. Integral under the heat flux density curve from immersion (t_o) until a specified time (t_x), which is proportional to the heat extracted, Fig. e - ∫qdt [MJ/m^2]
4. The time from immersion up to the moment when the core temperature (T_c) drops to 300 ^oC, which represents the rate of heat extraction from the core, Fig. a - $t_{Tc\ 300}$ [s]

The quenching intensity is bigger when the values q_{max} and ∫qdt are bigger, and the time intervals t_{qmax} and $t_{Tc\ 300}$ are shorter!
Generally, there is a good correlation between the quenching intensity, evaluated as described, and the resulting depth of hardening. Bigger quenching intensity produces bigger depth of hardening!

In addition, when comparing the curves obtained by different quenching tests, the described thermodynamic functions enable to get valuable information about:

- Whether the quenching process is a conventional quenching process, or a delayed quenching process.
  This depends on the time when the maximum heat flux density occurs (t_{qmax}), Fig. b.
- How big thermal stresses can be expected, and in which time interval; consequently how big residual stresses and distortion can be expected. This depends on the temperature differences shown in Fig. d.
- How big is the risk of possible crack formation during quenching. This depends on temperature at which the maximum heat flux density occurs (T_{qmax}), Fig. c.
  The lover the value of T_{qmax} , the higher is the risk of crack formation, especially with steels having high M_s temperature.

<u>Benefits of the system:</u>

- The first important benefit of using this system is the possibility to create *Own Data Base of Quenching Intensities*, that the user is creating by performing quenching tests with the Liscic/Nanmac probe in his own quenching facilities, under different quenching conditions. By comparing data for different tests stored in the own data base, the user can select the optimum quenching conditions, for his real case.
- The second very important benefit is the possibility to calculate the real heat transfer coefficient [W/m^{2}K] as function of time or as function of surface temperature. This is the first unavoidable step for every computer modelling of a quenching process. Once you have the heat transfer coefficient, by using a simple computer programme for direct heat conduction, you can calculate the relevant cooling curve in each arbitrary chosen point of cylindrical cross-sections of different diameters. By means of the relevant CCT diagram, of the steel grade in question, one can predict the microstructure and hardness after quenching under real quenching conditions.

Using more advanced proprietary computer programme, one can predict the quench-hardness distribution within the whole volume of axially symmetric workpieces of any shape.

<u>Remark:</u>

Instead of measuring the surface temperature directly by the Liscic/Nanmac probe, the surface temperature can be calculated using the Finite Elements (FE) inverse heat conduction method, based on a cooling curve measured in a point close below the surface. The Liscic/Nanmac probe was developed for scientific research purposes only, and it is not commercially available. Instead a similar probe, with the same function, based on the cooling curve measured at 1.0 mm below the surface, is developed.