THEORETICAL-EXPERIMENTAL DETERMINING OF COOLING TIME ($t_{8/5}$) IN HARD FACING OF STEELS FOR FORGING DIES

by

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This paper investigates the accuracy of analytical, empirical, and numerical expressions, i. e. the most favourable methods for calculating the cooling time from 800 to 500 °C ($t_{8/5}$). The degree of accuracy of time $t_{8/5}$ is very significant, because it determines the cooling rate, and consequently the structural changes in heat affected zone for hard faced layers. Based on the presented results, one can conclude that the finite element method provides the best conformity with the experiment and among analytical and empirical formulas the same goes for the expression of Japanese authors, for the case of hard facing of plane and prismatic parts.

Key words: *cooling time ($t_{8/5}$), temperature cycle, temperature field, hard facing, input heat, empirical formulas, finite elements method*

Introduction

At both welding and hard facing of low-alloyed and constructional steels, especially tempered ones, it is not sufficient to determine the technological parameters only, but also to take into account the influence of heat input on the heat affected zone (HAZ). The influence of temperature cycle on hardness increase is considered firstly, but change of mechanical properties, susceptability to cracking, *i. e*. the appearance of unfavourable structures, residual stresses and strains should be considered as well, all related with temperature field around the heat source and temperature change rate from 800 to 500 °C.

Since the cooling rate is variable and decreases with the temperature decrease, the cooling time from 800 to 500 °C ($t_{8/5}$) is taken as the parameter, which best characterizes cooling conditions of the HAZ, with respect to the lowest stability of the austenite. Types of structural transformations and properties of the HAZ depend to the greatest extent on the maximum reached temperature ($T_{max.}$) at certain zones of the HAZ and time $t_{8/5}$. The layer of the HAZ, which is in the immediate vicinity of the hard faced layer, reaches the highest cooling rate,

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which causes the highest hardness and proneness to cold cracks, and the lowest toughness. That is why the most unfavourable properties of the HAZ are determined by taking into account the temperature cycle below the hard faced layer.

In order to determine the cooling time from $t_{8/5}$ different methods are available, including analytical, numerical and experimental ones. In this paper several analytical methods have been applied, the finite element analysis as the most suitable numerical method and measurement of temperature by thermocouples in order to get the complete overview of the problem hard facing of forging dies. Starting point is in any case, the heat conduction analysis.

Basic equations of heat conduction

The problem of heat conduction is presented here briefly. Starting point is the equilibrium equation:

$$\frac{\mathrm{d}Q}{\mathrm{d}t} = \frac{\mathrm{d}U}{\mathrm{d}t} \tag{1}$$

where dQ and dU represent changes of heat and internal energy in volume dV in time interval dt.

Conduction of heat through solid bodies is defined by Fourier's Law:

$$q_j = -k_j \frac{\partial T}{\partial x_j}, \quad j = 1, 2, 3 \text{ no sum on } j \tag{2}$$

where q_j is the specific heat flux, k_j – the conduction coefficient, and $\partial T/\partial x_j$ the temperature gradient at direction x_j.

By simple algebra one gets the following differential equation:

$$\rho c \frac{\mathrm{d}T}{\mathrm{d}t} - \sum_{j=1}^{3} \frac{\partial}{\partial x_j}\left(k_j \frac{\partial T}{\partial x_j}\right) - q = 0 \tag{3}$$

where ρ is the material density, c – the specific heat at constant pressure, and q – the volumetric heat source.

General solution of differential equation of the heat conduction contains undefined functions and constants [1, 2]. The solution of temperature field $T(x_1, x_2, x_3, t) = T(x, y, z, t)$, must satisfy given initial and boundary conditions. The initial conditions define the distribution of temperatures at initial moment, $t = 0$:

$$T = T_s(x, y, z, 0) \tag{4}$$

The boundary conditions in general case are:

– prescribed temperature on S_1

$$T = T_s(x, y, z, t)$$

– prescribed flux on S_2

$$q_n = q_n(x, y, z, t)$$

– prescribed convection on S_3

$$q_h = h(T_0 - T_s)$$

– prescribed radiation on S_4

$$q_r = h_r(T_r - T_s)$$

where S_1, S_2, S_3, and S_4 are parts of surface, T_s is the temperature on the surface, q_n, q_h, and q_r are fluxes through surface, T_0 is the temperature of the surroundings, h – the transfer coefficient, h_r – the radiation coefficient, and T_r – the temperature of radiation source.

Analytical, empirical, experimantal, and numerical determining of the cooling time ($t_{8/5}$)

The cooling time can most accurately be determined experimentally from the measured temperature cycle curve, or with somewhat lesser or greater accuracy, based on analytical, empirical or numerical calculation of temperature cycles.

Rikalin's analytical method

When determining temperature fields in welding, differential eq. (3) can be transformed and adjusted to given conditions. That refers to various thicknesses of plates (thin or thick) and heat sources (moving or static) [3-9]. In this paper the hard facing is represented by the case of the semi-infinite body and the moving heat source with the constant velocity *v* (fig. 1).

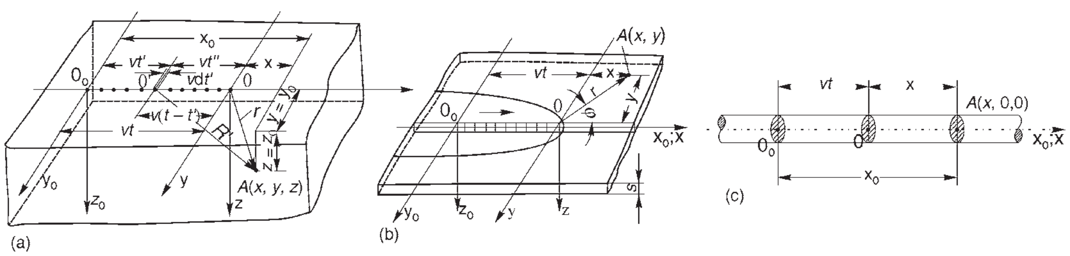


Figure 1. Basic forms of schematics in the case of the moving heat source

The temperature distribution in the case of the source which is moving with high velocity *v* along the coordinate $x = vt$, is given as:

$$T_{r,x} \quad \frac{q}{2\pi kr}\exp \quad \frac{vx}{2a} \quad \frac{vr}{2a} \tag{5}$$

where $r = (x^2 + y^2 + z^2)^{1/2}$ is the radius, $a = k/cp$ – the coefficient of thermal diffusivity, q – the effective power of the arc ($q = UI\eta$), and η – the heat efficiency ratio.

In the case of a thick plate expression (5) is transformed into the following form:

$$T_{y,z,t} \quad \frac{q}{2\pi kvt}\mathrm{e}^{\frac{r^2}{4at}} \tag{6}$$

In the case of a thin plate (fig. 2), the temperature distribution is calculated according to:

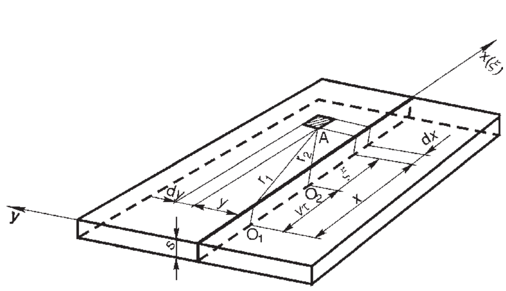


Figure 2. Hard facing of the thin plate of infinite dimensions

$$T_{y,t} \quad \frac{q}{vs\sqrt{4\pi kct}} \mathrm{e}^{\frac{y^2}{4at} bt} \quad \frac{q}{s\sqrt{4\pi kct}} \mathrm{e}^{\frac{y^2}{4at} bt} \tag{7}$$

where $q_1 = q/\mathrm{v} = UI\eta/v$ [J/cm], is the input heat, $b = 2h/cs\rho$ – the constant which defines the heat transferred to environment [3, 6, 8, 9], and h is the coefficient of the heat transfer.

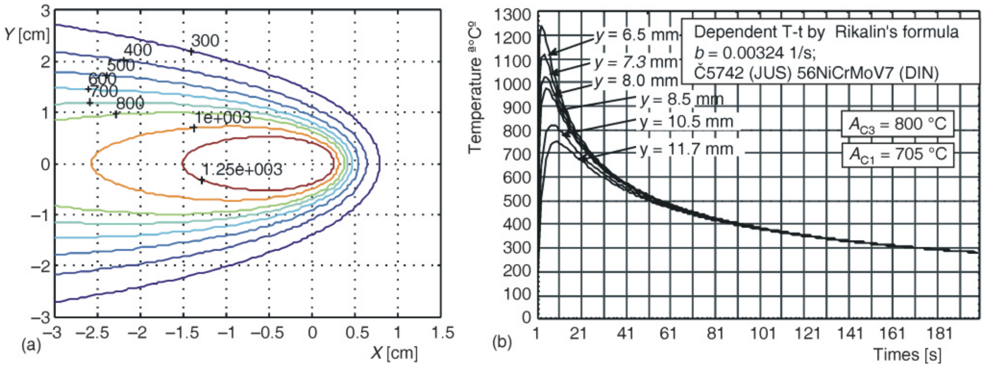
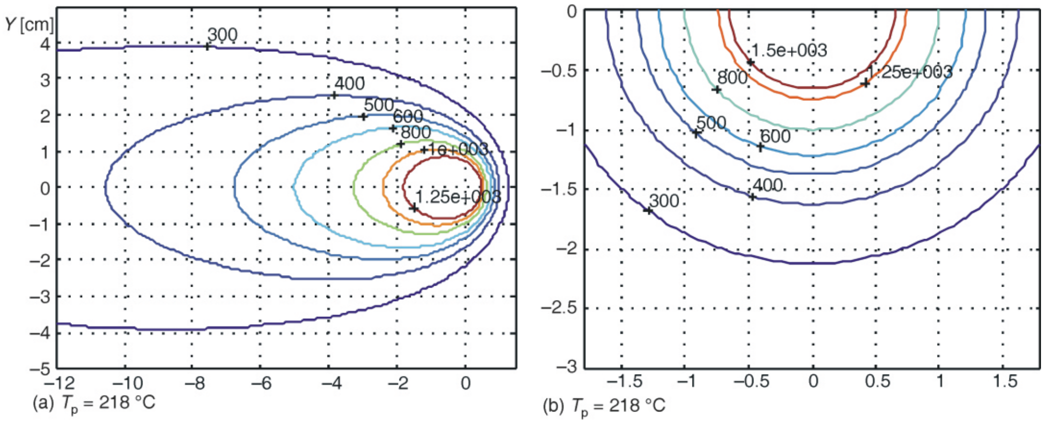


Figure 3. (a) Temperature field around the hard faced layer; (b) Temperature cycles of points in the HAZ (*s* = 7.4 mm; q_l = 8543 J/cm; T_p = 300 ºC; filler metal – UTOP 38; Ø3.25 mm) [3, 10]



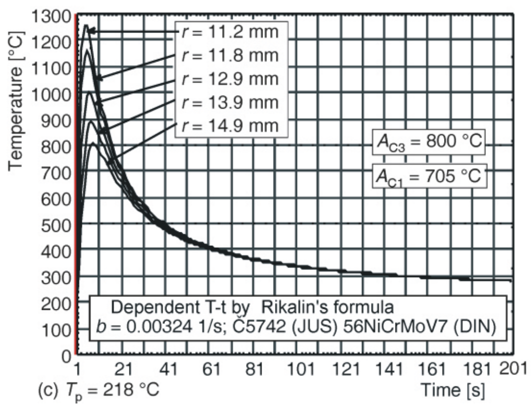


Figure 4. (a) Temperature field around the hard faced layer, (b) Temperature distribution along the plate cross-section, (c) Temperature cycles of individual points in the HAZ of the hard faced layer, (*s* = 29 mm, q_l = 28049 J/cm, filler metal - UTOP 55, Ø5.0 mm) [3, 10]

In calculating the temperature fields and temperature cycles, according to Rikalin's expressions [14], the computational software was applied (Matlab, Statistica), and for processing of results the programming languages (Fortran and Pascal), were used. By application of the expressions (5-7) the temperature cycles were calculated for the corresponding input heat and some points below the hard faced layer. Results are presented in figs. 3 and 4. All data used for calculation is given in figs. 3 and 4.

Calculation of cooling time ($t_{8/5}$) on the basis of empirical formulas

Out of many empirical formulae for calculation of cooling time ($t_{8/5}$), those based on the limiting sheet thickness and so-called Japanese authors' formula [11] are the most frequently used.

Calculation of $t_{8/5}$ based on limiting sheet thickness, $t_{8/5} = f(s_{gr})$

Limiting thickness, or the transition thickness between the thin and thick sheets was adopted by changing the way of the heat transfer from two- to three-dimensional. Two-dimensional heat transfer is related to thin sheets; it is assumed that the temperature is constant over the whole thickness of the hard faced part ($\partial T/\partial z = 0$). On the contrary, for thick sheets the temperature also varies over the thickness ($\partial T/\partial z \neq 0$). The limiting thickness is determined according to expressions:

$$s_{gr} = \sqrt{\frac{q_1 N_3}{2\rho c}\left(\frac{1}{500 - T_0} + \frac{1}{800 - T_0}\right)}\ , \text{cm} \tag{8}$$

Expression (8) shows that, for the given base metal, the limiting thickness depends on the input heat, type of the welded joint and initial temperature of the hard faced parts. The time, $t_{8/5}$, is given by the following expression:

– for thin sheets ($s \le s_{gr}$)

$$t_{8/5} = \frac{q_1^2 N_2}{4\pi\lambda\rho c s^2}\left[\left(\frac{1}{500 - T_0}\right)^2 - \left(\frac{1}{800 - T_0}\right)^2\right],\ \text{s} \tag{9}$$

– for thick sheets ($s > s_{gr}$)

$$t_{8/5} = \frac{q_1 N_3}{2\pi\lambda}\left(\frac{1}{500 - T_0} - \frac{1}{800 - T_0}\right),\ \text{s} \tag{10}$$

where N_2, and N_3 are factors of the joint shape [7, 11-14] and T_0 is the initial or the preheating temperature (T_p). Thermo-physical constants depend on the material and vary with temperature. They could be adopted, with sufficient accuracy, for the average value of the temperature interval 800 to 500 °C, *i. e.*, for 650 °C. The factors of the joint shape serve for correction, where the known empirical fact that cooling rate of the welded joint depends on both the thickness and on the type of the welded joint, is taken into account. For the case of hard facing these factors are considered to be equal to 1 ($N_2 = N_3 = 1$).

Calculation of the cooling time $t_{8/5}$ based on the Japanese authors' formula [11]

According to those authors the following formula is used:

$$t_{8/5} = \frac{k q_1^n}{\beta (T_{sr} - T_0)^2 \left[1 + \frac{2}{\pi} \operatorname{arctg}\left(\frac{s - s_0}{\alpha}\right)\right]}, \text{s} \tag{11}$$

The other data, necessary for calculation of the cooling time $t_{8/5}$ are given in [3, 7, 11, 13, 14].

Experimental determination of temperature cycles in hard facing

Temperature cycles in hard facing of steels operating at elevated temperatures – Č5742

In order to determine the cooling rate as accurately as possible, the special plates – models were prepared [3]. Plates were tempered and the corresponding holes for temperature measurements were drilled. Temperatures were measured by thermocouples (from the class of the K, NiCr-NiAl type, with diameter of 0.24 and 0.4 mm) [3].

In tabs. 1 and 2 experimentally obtained results are shown, compared with calculated ones, for different values of input heat, with and without preheating. In hard facing of thin plates, s = 7.4 mm, the hard facing parameters were within the following ranges: input heat, q_l = = 9663-16911 J/cm, hard facing velocity, v_z = 0.238-0.136 cm/s, and preheating temperature, T_p = = 20-280 ºC (filler metal - UTOP 38; Ø3.25 mm) [3, 10]. In hard facing of thick plates, s = 29 mm, the parameters were within the following ranges: q_l = 16500-32738J/cm, v_z = 0.258-0.130 cm/s and T_p = 20-355 ºC (UTOP 55; Ø5.0 mm) [3, 10].

Table 1. Comparative values of the cooling time $t_{8/5}$ (s = 7.4 mm, I = 115 A, U = 25 V, q_{ef} = 2300 W)

Hard facing velocity, v_z [cm/s]	Hard facing input heat, q_l [J/cm]	Preheating temperature, T_0/T_p [ºC]	Cooling time, $t_{8/5}$, [s]			
			Eq. (11) $(t_{8/5})^J$	Eqs. (8) and (9) $(t_{8/5})^{Sgr}$	$(t_{8/5})^{EXP}$	Eqs. (6) and (7) $(t_{8/5})^R$
0.238	9663	20	8.62	24.00	14.50	16.5-20
0.220	10560	20	9.85	29.0	17.00	20-21
0.186	12192	20	13.34	43.63	16.00	24-26
0.172	13372	273	44.20	273.9	28.00	88-90
0.169	13609	280	47.35	304.50	34.00	94-98
0.136	16911	185	39.00	206	23.50	70-76
0.208	11058	180	20.1	84.9	27.00	42-50
0.190	12105	178	22.80	100.3	23.00	48-54
0.183	12568	178	24.05	107.3	19.00	48.5-57
0.215	10698	169	18.19	73.4	19.50	36-43
0.150	15333	180	32.90	163.2	24.50	59-68

Comparison of the results is also shown in figs. 5 and 6, and the characteristic form of the temperature cycles, obtained experimentally, in fig. 7.

Table 2. Comparative values of the cooling time $t_{8/5}$ (s = 29 mm, I = 190 A, U = 28 V, q_{ef} = 4256 W)

Hard facing velocity, v_z [cm/s]	Hard facing input heat, q_l [J/cm]	Preheating temperature, T_0/T_p [°C]	Cooling time $t_{8/5}$, [s]			
			Eq. (11) $(t_{8/5})^J$	Eqs. (8) and (9) $(t_{8/5})^{Sgr}$	$(t_{8/5})^{EXP}$	Eqs. (6) and (7) $(t_{8/5})^R$
0.148	28757	20	11.20	14.10	16.0	10.8-12.5
0.130	32738	355	76.17	287.50	78.0	70.5-74.5
0.161	26436	231	24.36	47.30	25.0	24-27
0.152	28049	218	24.80	47.80	22.0	23.2-25.5
0.258	16500	204	10.43	14.89	12.0	13.5-14.5
0.167	25414	178	17.60	28.80	16.0	18-20
0.185	23000	235	20.20	37.10	20.5	21-23.5
0.257	16912	204	10.83	17.52	12.00	13.60-14.70

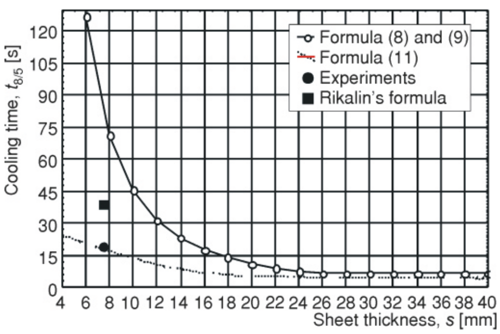


Figure 5. Comparative results of the cooling time (s =7.4 mm, d_e = 3.25 mm, T_p = 169 °C, q_l = 10698 J/cm)

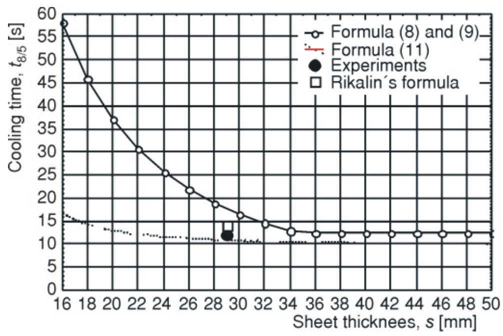


Figure 6. Comparative results of the cooling time (s = 29 mm, d_e = 5 mm, T_p = 204 °C, q_l = 16912 J/cm)

Numerical method (FEM) of determining the cooling time $t_{8/5}$

On the basis of of equilibrium equation for heat conduction (3), the following can be written:

$$\int_V \rho c h_I \frac{dT}{dt} dV \quad \int_V h_I \sum_{j=1}^{3} \frac{\partial}{\partial x_j} \left(k_j \frac{\partial T}{\partial x_j} \right) dV \quad \int_V h_I q dV \quad 0 \tag{12}$$

where h_I are interpolation functions for the finite element.

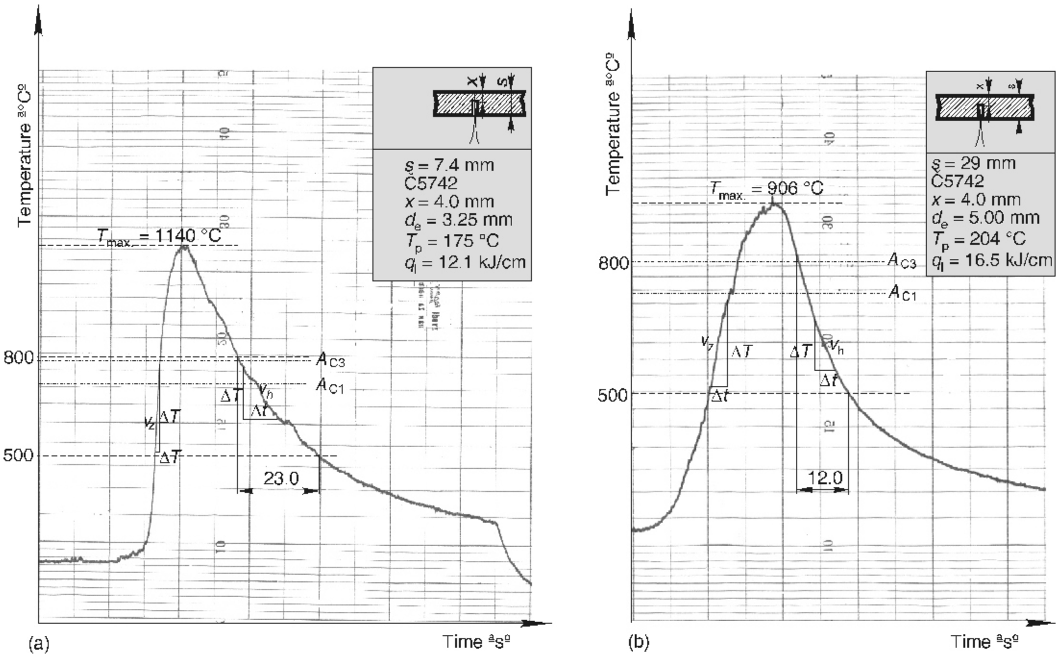


Figure 7. Temperature cycles of the hard faces layer HAZ
(a) thin sheet, (b) thick sheet

Temperature T in element is given as:

$$\mathrm{T} = \mathrm{HT} \tag{13}$$

where H is the matrix of interpolation functions and T – column matrix of temperatures in nodes.

The following eq. (14) represents the equation of energy balance of finite element in the case of 3-D non-stationary heat conduction.

$$\mathrm{C}\dot{\mathrm{T}} \quad \mathrm{KT} \quad \mathrm{Q} \tag{14}$$

where matrices C and K and column matrix Q are determined as:

$$\mathrm{C} \quad \int_V \rho c \mathrm{H}^T \mathrm{H} \mathrm{d}V \tag{15}$$

$$\mathrm{K} = \mathrm{K}^{\mathrm{k}} + \mathrm{K}^{\mathrm{h}} + \mathrm{K}^{\mathrm{r}} \text{ and} \tag{16}$$

$$\mathrm{Q} \quad \mathrm{Q}^{\mathrm{q}} \quad \mathrm{Q}^{\mathrm{q_n}} \quad \mathrm{Q}^{\mathrm{h}} \quad \mathrm{Q}^{\mathrm{r}} \tag{17}$$

By using the surface interpolation row matrix H^s, the proper matrices and column matrices can be written in te following form in eqs. (16) and (17):

$$\mathrm{K}^k \quad \int_V \mathrm{B}^T \mathrm{kBd}V \tag{18}$$

$$\mathrm{K}^h \quad \int_S h\mathrm{H}^{sT} \mathrm{H}^s \mathrm{d}S \tag{19}$$

$$\mathrm{K}^{r} \quad {}_{S}\, h_r \mathrm{H}^{sT}\mathrm{H}^{s}\mathrm{d}S \tag{20}$$

$$\mathrm{Q}^{q} \quad {}_{V}\, q\mathrm{H}^{T}\mathrm{d}S \tag{21}$$

$$\mathrm{Q}^{q_n} \quad {}_{S}\, q_n \mathrm{H}^{sT}\mathrm{d}S \tag{22}$$

$$\mathrm{Q}^{h} \quad {}_{S}\, hT_0 \mathrm{H}^{sT}\mathrm{d}S \tag{23}$$

$$\mathrm{Q}^{r} \quad {}_{S}\, h_r \mathrm{T}_r \mathrm{H}^{sT}\mathrm{d}S \tag{24}$$

Calculation of cooling time $t_{8/5}$

For analyzing the cooling time $t_{8/5}$, the two space (3-D) models were formed (one for the thin, s = 7.4 mm and the other one for thick the sheet metals, s = 29 mm), which are based on the application of finite elements method (FEM). Since the problem is plane-symmetrical, it is sufficient to consider only one half of the model.

For modeling of sheet metals, the mesh of eight-node 3-D finite elements was used. For the thin sheet metal, the mesh of 25476 nodes and 20160 elements was developed, while for the thick sheet metal the mesh of 41184 nodes and 35805 elements was formed. It should be pointed out that, in analytical calculations, the difference between thin and thick sheet metals is that for thin sheet metals, two-directional heat conveyance is presumed, *i. e.* $T \quad s = 0$ is adopted, while for thick sheet metals, the change of temperature with thickness is taken into consideration as well, *i. e.* $T \quad s \quad 0$. In both cases, real preheating temperature is employed, and the thermal properties, namely the conductivity, k, and the product of specific heat, c_p, and the material density, ρ, are taken as average value in the temperature range of 20-700 °C (k = = 36 W/m°C, $c_p \rho$ = 4898556 J/m^3°C) [5, 15].

Heat is conveyed to sheet metal material according to Gauss' distribution and is given as:

$$q_2 \quad q_{2m}\mathrm{e}^{\ \ kr^2} \tag{25}$$

where q_{2m} is the flux at point r = 0, k = 3 is the constant, and r is the radius of heat effects [5, 6, 9, 16].

For the solution of this problem, it was necessary to make a special programme which would provide the given distribution of flux per elements with maintaining the previously mentioned distribution. Therefore, the heat quantity conveyed from electric arc must be distributed per elements in radius r, the direction of which corresponds to projection of electrode tip on hard faced part.

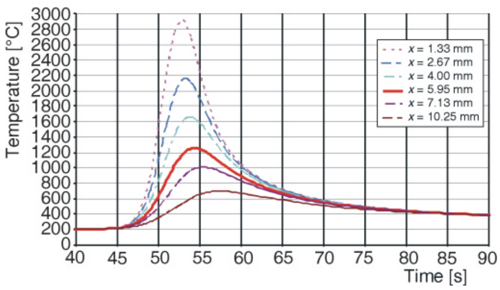


Figure 8. Temperature cycles of some zones of hard faced layer (s = 29 mm, q_l = 16500 J/cm, v_z = 0.258 cm/s, T_p = 204 °C)

Results of calculation of cooling time

The obtained results are presented in figs. 8 to 11 as temperature cycles, used to determine cooling time, and in figs. 12 and 13 as temperature fields.

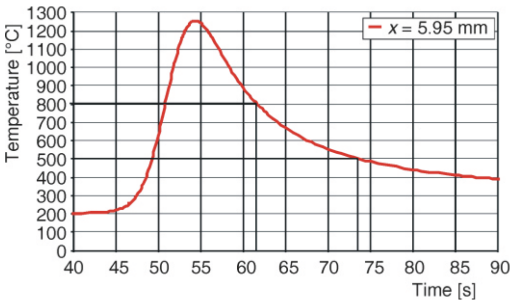


Figure 9. Temperature cycle of HAZ hard faced layer (s = 29 mm, q_l = 16500 J/cm, v_z = 0.258 cm/s, x = 7.13 mm, T_p = 204 °C)

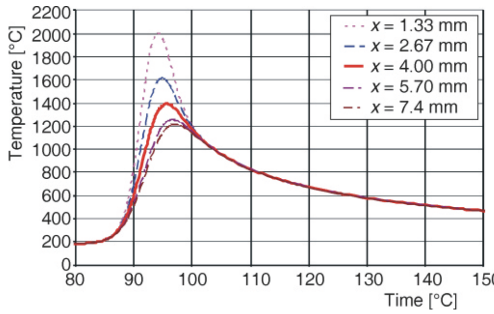


Figure 10. Temperature cycles of some zones of hard faced layer (s = 7.4 mm, q_l = 11058 J/cm, v_z = 0.208 cm/s, T_p = 180 °C)

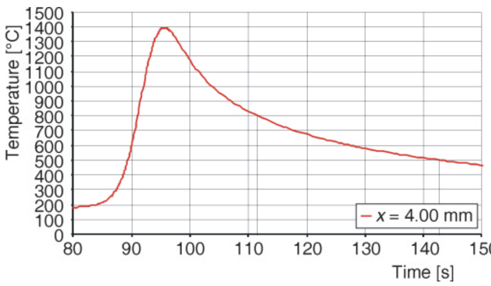


Figure 11. Temperature cycle of HAZ hard faced layer (s = 7.4 mm, q_l = 11058 J/cm, v_z = 0.208 cm/s, x = 4 mm, T_p = 180 °C)

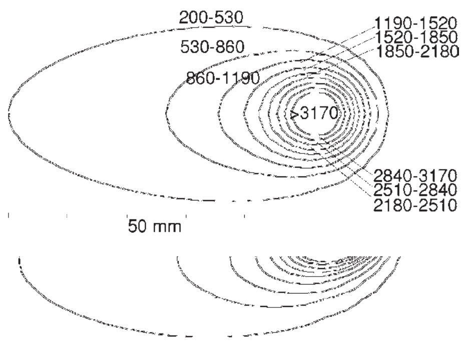


Figure 12. Temperature field, (a) from above, (b) sideways (s = 29 mm, q_l = 16500 J/cm, v_z = 0.258 cm/s, T_p = 204 °C, at depth of 7.13 mm)

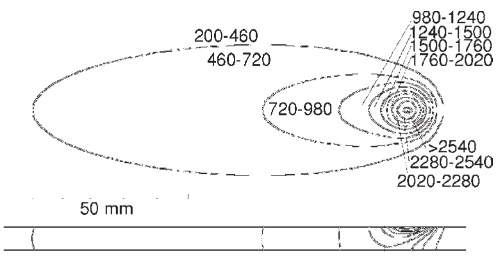


Figure 13. Temperature field, (a) from above, (b) sideways (s = 7.4 mm, q_l = 11058 J/cm, v_z = 0.208 cm/s, T_p = 180 °C, at depth of 4 mm)

In two-dimensional figs. 12 and 13 temperature fields from which temperatures can be read off are given around moving source. The knowledge about these distributions is highly significant for determining material properties in those zones which are exposed to the influence of heat input.

Discussion and conclusions

Typical results for the parameter $t_{8/5}$ are shown in tabs. 4 and 5, taken from tabs. 1 and 2 as given for the optimal welding parameters, and including the FEM results for the same input data. By comparing the results shown in tabs. 4 and 5, the major (intolerable) differences are observed between the cooling time calculated according to formula $t_{8/5}$= f(s_{gr}) and experimental results. The best conformity with experimental results is achieved by numerical method and formula of Japanese authors. This conclusion refers to hard facing of the flat sheets, while other forms of hard faced surfaces are yet to be analyzed.

Table 4. Comparative values of cooling time *s* = 29 mm

q_l, [Jcm^{-1}]	T_p, [°C]	Cooling time $t_{8/5}$, [s]				
		$(t_{8/5})^J$	$(t_{8/5})^{Sgr}$	$(t_{8/5})^{EXP}$	$(t_{8/5})^R$	$(t_{8/5})^{FEM}$
16500	204	10.43	14.89	12	13.5-14.5	11.5

Table 5. Comparative values of cooling time *s* = 7.4 mm

q_l, [Jcm^{-1}]	T_p, [°C]	Cooling time $t_{8/5}$, [s]				
		$(t_{8/5})^J$	$(t_{8/5})^{Sgr}$	$(t_{8/5})^{EXP}$	$(t_{8/5})^R$	$(t_{8/5})^{FEM}$
11058	180	20.1	84.9	27	42-50	31

Based on the presented results, one can conclude that the finite element method provides the best conformity with the experiment and among empirical formulas the same goes for the expression of Japanese authors, for the case of hard facing of planar and prismatic parts. By applying the specified information, the cooling time in critical temperature interval can be determined with sufficient accuracy, without the complex and expensive experimental procedure.

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