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CHANGES OF THE METAL TEMPERATURE AT THE AXIAL WATER-AIR COOLING OF CYLINDRICAL SAMPLES

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В роботі показані результати експериментальних досліджень впливу витрати води у водо-повітряному спрейєрі на швидкість охолодження зразків зі сталі 42CrMo4 з температури аустенитізації. Проаналізовані температурні поля для різних умов охолодження. Експерименти проводилися для охолодження циліндричних зразків з торця.
Ключові слова: *водо-повітряне охолодження, інтегровані металургійні технології.*

The results of experimental investigations of the influence of water consumption in the water-air sprayer at the rate of cooling of the specimens of steel 42CrMo4 with quenching were given. The temperature fields by the cooling rate criterion were analyzed. Experiments were carried out for bottom quenching of cylindrical specimens.
Key words: *water-air spray cooling, integrated metallurgical technologies.*

Objective. The advantages of spray cooling are its versatility, the possibility of integration in technological processes of metal forming, as well as low power consumption (in comparison with laser hardening) and lack of harmful environmental emissions. The main objectives of this process are: to obtain an adjusted distribution of hardness and mechanical properties in the cross-section of products, to correct the distortion (because of deformation and temperature irregularity on the elements of product), to prevent the appearing of undesirable phases in the structure of metal. Efficiency of spray cooling, according to [1] can be evaluated by the time - temperature fall curves on the surface and the central part of the product (sample) depending on the parameters of water-air cooling.

Analysis of problem. Analysis of the publications [1, 2 and others] as well as authors own experience (obtained in the project SFB 489 "Prozesskette zur herstellung präzisionsgeschmiedeter hochleistungsbauteile" [3]) showed that the processes of spray cooling in most cases are examined in position of the direct influence of its parameters on the metal properties, or directed at determining of the heat transfer coefficient in a particular technological process (which is used in further calculations). On the other hand, the behavior of a metal (in particular changing its phase structure) is usually described with termokinetics diagrams (in coordinates of "time - temperature"). For determining steel hardenability is used "Jominy end quench test" (according to EN ISO 642 : 1999). Unfortunately, this test does not account the fall of the cooling intensity in the radial direction, which is typical for sprayer cooling. Thus, the well-known approaches to the description of the temperature change in the sprayer cooling processes are not free from the influence of material properties, limitations associated with the geometry of the object (sample) and technological features of sprayer design. We also can not completely ignore these parameters at description of changes in temperature. However, we will make an attempt to systematize aspects of this influence by accepting certain assumptions and implementation of additional experimental studies.

Purpose of the study. The purpose of this study is description of changes of metal temperature over time depending on the parameters of water-air sprayer cooling. This description allows determining the effect of design parameters of sprayer, the geometric parameters of flow and sample. In turn, this allows considering these parameters at calculating of cooling conditions (which directed to achieve required cooling rate for obtaining the adjusted structure and properties of the metal, both on surface and inside of sample.

Description of studies. Experiments for determining the change of metal temperature in the cooling process were carried out in the Institute of Materials Science of Leibniz University Hanover, where was created and is used an experimental device for the physical simulation of the processes of hardening and hardening with tempering [4]. This device consists of a heating resistance furnace, cooling module with water- air nozzles from company "Spraying Systems" 2850 (D1) and 60100 (D2), as well as the kinematic module controlled by a computer. The temperature distribution at the axial cooling of cylindrical sample (diameter 60 mm and thick 42 mm, (Fig. 1) made of 42CrMo4 (EN 10083) was investigated.

The area of cooling surface was 2826 mm^2, the volume of sample - 118692 mm^3. The temperature was measured with a chromel – alumel thermocouples (type "K" with a diameter of 0,5 mm). Measurement frequency – 0,5 Hz. For each experiment were being used six thermocouples (TE1...TE6) located radially at interval of 5 mm; the thermocouple TE6 was placed in centre of sample`s cross-section. There are two series of experiments has been carried out. Thermocouples were placed at a distance of 1 mm and 5 mm from the cooling surface during these experiments. In both cases, the heating temperature of the samples was 980 ° C. Temperature loss on the sample surface during transfer from the furnace to the cooling device (8-12 sec) equalled 40...80 ° C (at a depth 1 mm), and - 30...50 ° C (at a depth of 5 mm). The distance from the nozzle to the cooling surface in all experiments was 100 mm. Air consumption during the experiments was not measured. Time of spaying equalled 100 seconds (for experiments with water-air cooling) and 200 seconds (for experiments with only air cooling). Cooling modes are shown in Table 1.

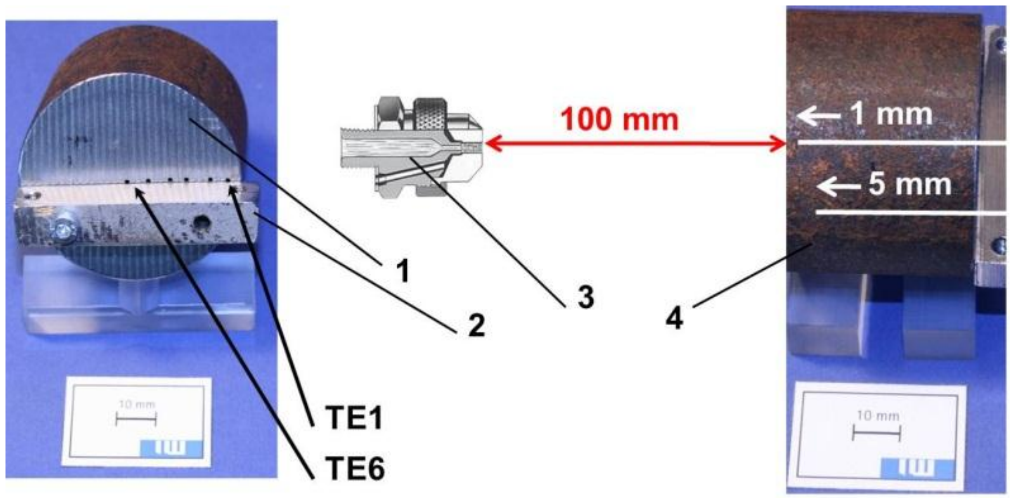

Figure 1. Placement of the thermocouples inside the samples at axial spray cooling: 1 – sample (view on the side opposite the cooling surface); 2 – thermocouple clamp; 3 – schematic representation of water-air nozzle; 4 – sample (side view)

Table 1. Relative water consumption at different cooling modes

Cooling mode	0W6L*	2W2L	3W3L	4W3L	5W3L	3W3L
Nozzle type	D1					D2
Relative water consumption, gr./sec	0	2,63	3,13	5,47	7,80	18,37

** cooling only with air*

Results of study

1. Investigation of the temperature distribution on the cross section of the sample. Results of investigation showed that these thermocouples TE1...TE6 (placed concentrically at a distance 1 mm and 5 mm from the cooling surface) allows to estimate the values of temperatures at each moment of cooling. Changing the values of temperatures at one and the same time for all modes of cooling near the cooled surface (1 mm) for the experiments can be considered proportional to the distance between points of measurements with sufficient accuracy. I.e. the temperature (according to the thermocouple data located at the distance *x* from the centre of the sample) can be determined by the relationship:

$$T_x = T_0 + kx, \quad (1)$$

T_0 – temperature according to the thermocouple data located at the axis of flow; *k* – proportionality factor (°C/mm); *x* – the distance from the axis of flow (mm).

Special studies to identify and verify the values of the coefficient *k* (1) for the temperature values obtained from all thermocouples have not been carried out. However, the values from thermocouple located at a depth of 1 mm at spraying mode 3W3L 9 (see Table 1) were been changed from 0 to 16. Moreover, the maximum values were in the area of temperature $T_0 \approx$ 400 ° C. The maximum values of absolute deviations of the calculated temperatures are reached to 60 ° C at the same temperature (≈ 400 °). Such proportional behaviour of temperature may indicate that the shape and spraying quality were at the high level.

For the thermocouple installed at a depth of 5 mm from the cooling surface the influence of no cooled surface has been observed. It was reflected in the fact that at the cooling mode 3W3L values of the coefficient *k* (1) were been varied from 0 to 18 (basis of comparison – TE2...TE6 (T_0 = TE6 by (1)), while (on the basis of comparison ... TE1-TE2 (T0 = TE2 by (1))), these values were in some cases below zero. Area of maximal values also was about $T_0 \approx$ 400 ° C for this series.

In this case, an insignificant disturbance of proportionality of temperature change over cross-section was observed. However, the data is insufficient to conclude that the temperature falling becomes a "classic" exponential character. It should be noted, that the side (not cooled) surface of the sample also received the water cooling due to the spray flow turbulence. Therefore, the temperature distribution over the cross section of the sample requires further investigation for determining the limit of influence of the sprayer cooling, and cooling of the sample through the sides. Below (Table 2) will be given the values of maximum difference of temperatures in the area of values obtained with thermocouples TE1...TE6, temperature T_0, and the coefficient k, which was defined taken in account of that the distance between the outer thermocouples was 25 mm.

2. Effect of water consumption on the temperature change. According to the results of research (with the assumption that the temperature changes uniformly between the measuring points) the fields of possible temperature values for the planes at a distance of 1 mm and 5 mm from the cooling surface were constructed. Since these fields have a complicated shape, which is defined by the thermal processes occurring in the metal and inevitable errors during experiment, they describe qualitative influence of the relative water consumption (WV) on the cooling rate of the metal. For the obtaining quantitative dependences of the cooling rate from the spray parameters in these conditions it can be used temperature range (800...500 ° C). On the one hand, this interval is widely used for steel in the technique, and on the other hand - it is characterized by stable linear cooling process. Thus, according to the results of these experiments could be used characteristic $t_{8/5}$ (for the temperature field inside borders: TE1 (peripheral part of section) and TE6 (central part of section)) for assessment of influence of water consumption on the cooling rate implying that other values of $t_{8/5}$ will be also inside these borders. General view of the fields of possible temperature values at the distance of 1 mm and 5 mm from the cooled surface is shown in Fig. 2.

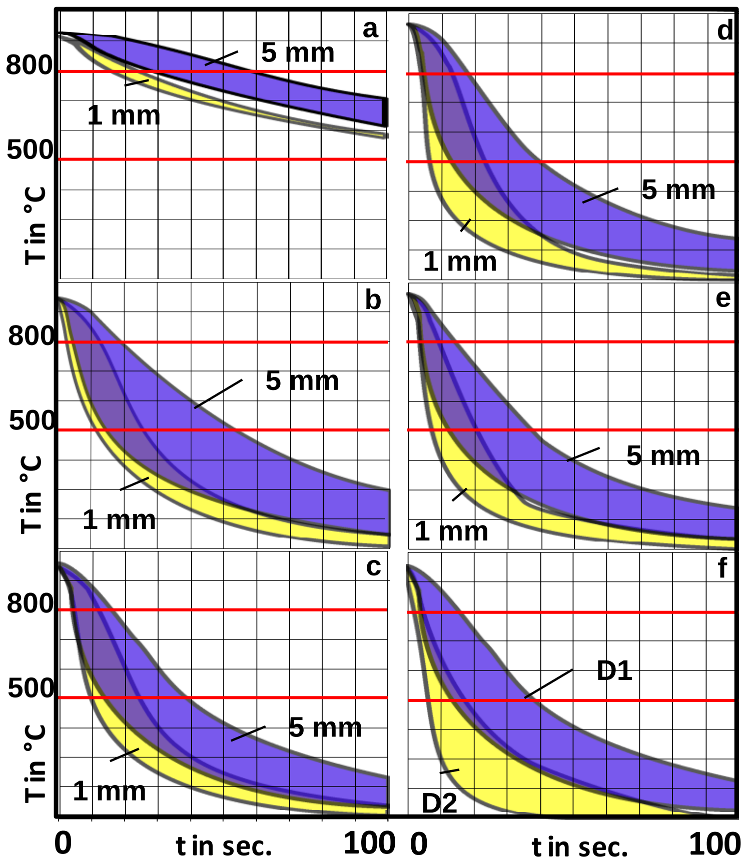

Figure 2. Fields of temperature (notations in 5.2)

The results of an experiment with cooling only by air (0,6 MPa) are presented in the Fig. 2a. The results of cooling at mode with relative water consumption from 2,63 to 7,8 gr./sec are presented in the Fig. 2b and Fig. 2e respectively. As can be seen from these figures, the increase of relative water consumption in this range does not carried out to a significant change in the view of temperature fields. Therefore, it was carried out additional experiment at mode 3W3L (Table 1) for the two types of nozzles (Fig. 2f), one of them (D1) was used in the previous experiments, and another (D2) provided in this spray mode relative water consumption at the level of 18,37 gr./sec. Temperature measurements in this experiment were carried out at a distance of 5 mm from the cooled surface (see Fig. 1).

3. Quantitative assessment of experiments results

The results of these studies for each cooling mode according to the data from thermocouples installed at a distance of 1 mm and 5 mm from the cooling surface are presented in Table 2.

Table 2. Values of experimenal results

Cooling mode		0W6L*		2W2L		3W3L		4W3L		5W3L		3W3L
Type of nozzle		D1		D1		D1		D1		D1		D2
WV in gr./sec		0		2,63		3,13		5,47		7,80		18,37
H in mm		1	5	1	5	1	5	1	5	1	5	5
T_{min}, °C	TE1	493	605	140	299	146	233	121	224	128	230	89
	TE6	485	510	123	146	110	125	95	121	102	108	51
$t_{8/5}$, c	TE1	148	n.d	13	37	12	21	10	21	11	23	10
	TE6	135	130	6	10	5	9	3,5	8	3	7	3
$v_{8/5}$, °C/c	TE1	2	n. d.	23,1	8,1	25	14,3	30	14,3	27,3	13	30
	TE6	2,2	2,3	50	30	60	33,3	85,7	37,5	100	42,9	100
ΔT_{max} °C		16,6	92,3	280,2	383,5	376,9	370,5	449,7	392,2	385,2	375,1	269,9
$T_{0TE6(\Delta tmax)}$ °C		896,9	719,1	508,5	393,6	424,6	404,5	387,9	413,7	377,4	449,1	247,5
k (°C/mm)		0,66	3,67	11,2	15,34	15,1	14,8	18	15,7	15,4	15	10,8

WV – water consumption in gr./sec;

h – distance from thermocouple to the cooling surface (Fig. 1) in mm;

T_{min} in °C – minimal temperature reached in 100 sec of sprayer working;

$t_{8/5}$ in sec. – time, in which the temperature values during cooling change from 800 to 500°C [5] according to the thermocouples;

$v_{8/5}$ in °C/c – cooling rate in the temperature range 800 ... 500 ° C;

ΔT_{max} in °C – the maximum difference of temperature according to the thermocouples TE1-TE6 (scatter of temperature values);

$T_{0(\Delta tmax)}$ in °C – the temperature according to the indication of TE6 (axis of nozzle) at which was obtained the value ΔT_{max} in °C.

k – coefficient of proportionality (see p. 1).

4. The interpretation of results

Change of the minimum temperature reached in 100 seconds of sprayer working depending on the water consumption is shown in Fig. 3.

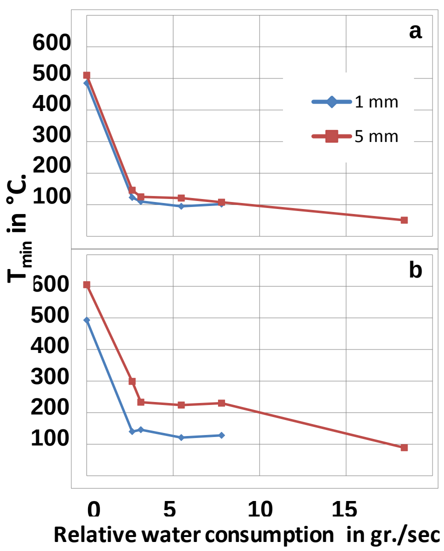

Figure 3. Dependence of the minimum reached in 100 seconds of spraying temperature on the relative water consumption; a) on the TE6 data (sample axis); b) on the TE1 data (peripheral part)

It should be noted a significant difference in cooling results with usage even small quantity of water in spray. Air cooling provides a temperature of 500...600 ° C, while using of water reduces this temperature to 100...300 °C. As can be seen from Fig. 3a, the difference between the reached temperatures is insignificant according to the thermocouples located at a depth of 1 mm and a depth of 5 mm. This demonstrates that the layer thickness of the intensively cooled metal exceeds 5 mm. It is known, that the minimum temperature for water-air sprayer cooling is 100 ° C – the temperature of pure water boiling. Further decreasing of metal temperature requires much more time and water.

Comparison of the data in Fig. 3a and 3b shows, on the one hand, that minimum reached temperatures of central and peripheral parts of sample are almost the same at a distance of 1 mm from the cooling surface (TE1-TE6 = 8...36 ° C) in the range of 600-100 °C for all modes of cooling. On the other hand at the distance of 5 mm from cooling surface the difference of these temperatures at the level (TE1-TE6 = 95...153 ° C) is observed and kept constant for all modes of cooling (except the case of using nozzle D2 (TE1-TE6 = 38 ° C)). The values of the coefficient *k* (p. 1) in this case are about 4 °C/mm.

6. Cooling at range of temperatures of 800...500 ° C

General provisions. The values of the cooling time in range of $t_{8/5}$,(see Table 2) show the difference between the air and the air - water cooling. This difference at the air cooling is significantly greater. For all cases of water-air cooling the time of temperature fall varies from 3 to 33 sec. More clearly the influence of the water consumption in sprayer illustrated with the rate of cooling $v_{8/5}$ (°C/sec) (Fig. 4).

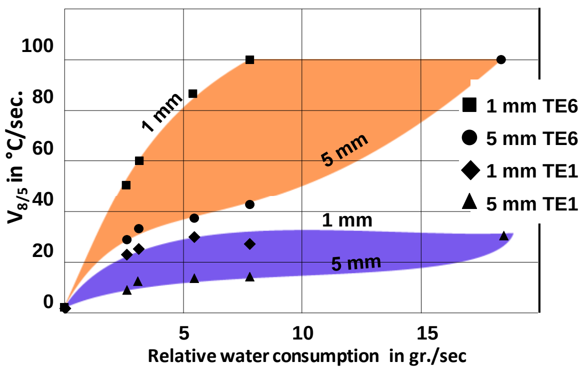

Figure 4. Dependences the cooling rate in the temperature range of 800...500 ° C from the relative water consumption

At determining the cooling rate was accepted that in this temperature range this rate is constant (temperature falling law is linear). It gives the overhead 50...60 ° C values of calculated with known rate and time of cooling temperatures. While the real cooling rate initially has higher values. This is due to the concave character of curve of temperature falling and it is true for curves of temperatures falling, obtained from the thermocouples placed on the nozzle axis (see Fig. 2). The curves of temperature falling (obtained from thermocouples placed at some distance from the axis of the nozzle) have a more linear character. With further retreat from the axis of the nozzle curves acquire more convex character (the error in this case reaches same 50...60 ° C only with "minus "). An increase of relative water consumption carries out to a stable increase of temperatures difference at the same time of cooling. This in turn carried out to an intensification of the heat output. Unfortunately, the experimental data now is not enough to explain this, so this question is the subject of further research.

Thus, one can be concluded that at increasing of the distance between the point of temperature measurement and axis of spray the character of variation of cooling rate is constant, changes only its intensity. At the same time, movement of the plane of temperature measurement into depth of the sample carries out to the inflection of curves of the cooling rate from the water consumption dependences. This fact requires further investigation.

Such a parameter as the cooling rate in the range of 800...500 °C can also be used as an additional tool for describing the character of the temperature fall during spray cooling. At the analysis of experimental data about the temperature falls it is a problem of determining the temperature of start of intensive cooling and zero point of time of its (starting point). Usually the data from thermocouples is begun to register before the beginning of spray cooling. For solving this problem, it can be used two ways.

First way. Determination of the time (t_{0e}) and temperature (T_{0e}) of intensive cooling beginning depending on changing of temperature fall according to the data from thermocouple (which is the closest to the cooling surface and the centre of the spray). This rate can be found according to the equation 2:

$$v = \frac{dT}{dt} \text{ [°C/sec.]}, \qquad (2)$$

dT – difference in the thermocouple readings for the time between measurements *dt*.

Such method gives accurate results when the measuring frequency is more than 10Hz. For example, at the measurements of temperature fall with the frequency of 10Hz the following values of cooling rate v (°C/sec) were obtained (Table 3).

Table 3. Examples of determining the starting point of intensive cooling

Example 1			Example 2		
t in sec.	T in °C	v in °C/sec	t in sec.	T in °C	v in °C/sec
15,8	930,6	1,56	20,2	936,7	4,29
15,9	930,5	3,51	20,3	936,3	4,29
16	930,1	44,44	20,4	936,7	53,79
16,1	925,7	513,38	20,5	931,3	365,649
16,2	874,3	1131,61	20,6	894,8	1041,57
16,3	761,2	1137,07	20,7	790,6	1222,05

t in sec. – time since the beginning of the measurement;

T in °C – readings of thermocouple mounted on the axis of flow at a depth of 1 mm from the cooling surface;

v in °C/sec. –cooling rate.

Based on practical experience it can be assumed that the beginning of intensive cooling corresponds to the first increase of rate in 50 times (t_{0e} = 16,1 sec from the beginning of temperature measurement for example 1 and t_{0e} = 20.5 sec – for example 2). For these examples the temperatures of beginning of intensive cooling (T_{0e}) amounted to 925,7 and 931,3 °C respectively.

Second way. Determining of the time and the temperature of beginning of intensive cooling depending on the cooling rate $v_{8/5}$ in °C/sec. This method is less accurate, but allows to determine the coordinates (t, T) of the start of spray cooling with a lower frequency of temperature measurements. It consists in the interpolation of rate graph $v_{8/5}$ to the intersection with the graph of temperature change according to the data of thermocouple (Fig.5). According to Fig. 5 for example 1: t_{0e} = 16,15 sec. and T_{0e} = 904 °C, for example 2: t_{0e} = 20,58 sec. and T_{0e} = 905 °C.

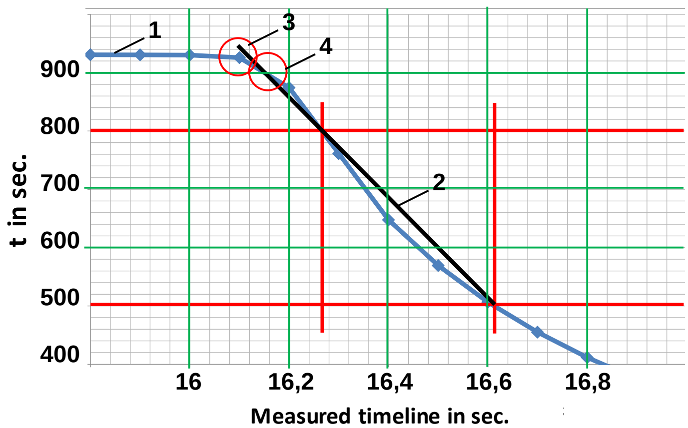

Figure 5. Example of determination of t_{0e} u T_{0e} values by cooling rate $v_{8/5}$: 1 – measured values; 2 – cooling rate $v_{8/5}$; 3 – t_{0e} value, determined by current cooling rate (first way); 4 – t_{0e}, value, determined by $v_{8/5}$ (second way)

The accuracy of this method depends upon such parameters: frequency of measurements, the location of the thermocouple (the maximum accuracy gives the temperature measurement in the point, which placed as soon as possible close to the intersection of the flow axis and cooled surface), as well as the interpolation method between the points of measurement. Interpolation of the graph 1 (see Fig. 5) with parabola give more accurate results. If the experiment involves several thermocouples located at different distances from the surface, then (for more far thermocouples from the intersection of flow axis and cooled surface) t_{0e} should be chosen the same like for the point, which is closest to the intersection of the flow axis and cooled surface. This allows determining the influence of the shape and size of the sample on the cooling rate. An important limitation of the application of both methods is the presence of significant difference between the rates of the cooling on the air and with the sprayer. Planned accuracy of t_{0e} determining for all researched cases of water-air spray cooling: ± 0,3 sec, and T_{0e} = ± 25 °C.

Using the method of the temperature determining of intensive cooling beginning it can be supplemented the missing data in Table 2.

Table 4 (table 2 continued). The start of spray cooling temperature

Mode of cooling	0W6L		2W2L		3W3L		4W3L		5W3L		3W3L
Type of nozzle	D1		D1		D1		D1		D1		D2
WV in gr./sec	0		2.63		3.13		5.47		7.80		18.37
H in mm	1	5	1	5	1	5	1	5	1	5	5
T_{0e} in °C	909	921	925	942	925	948	928	934	902	931	895

At analysis the data in Table 4 should be considered that the results for the distances h from the cooling surface (equal to 1 and 5 mm) were obtained in different experiments, in which the duration of transportation of the sample from the furnace to the cooling sprayer device was different.

CONCLUSIONS

The difference in temperatures at one and the same time for all modes of cooling near the cooled surface (1 mm) for the experiments can be considered proportional to the distance between points of measurements with sufficient accuracy. At a depth of 5 mm an insignificant disturbance of proportionality of temperature changing at the cross section has been observed. Therefore, the distribution of temperature at the cross section of the sample requires further investigation for determining the limits of influence of sprayer cooling and the cooling effect through the sides of the sample.

Due to complex shapes of curves of temperature fall for obtaining quantitative dependences of cooling rate from the parameters of sprayer cooling it is expedient to use the temperature interval (800...500 °C) for the steel samples.

For current conditions defined that the multiple increase of relative water consumption at sprayer water-air cooling gives not multiply increase of the cooling rate. The influence of relative water consumption on the cooling rate changes its character at the increasing of the distance from the cooling surface in the direction of the sample`s axis.

Increase of relative water consumption causes the growth of maximum variation of temperature values till the attainment of maximum, then follows flowing decrease of this variation. This is due to the fact that at first the intensity of heat sink (cooling rate) along the plane of the placement of thermocouples and into the sample and has the same character, then the intensity of the heat sink increases in the plane parallel to the axis of the nozzle.

The actual trends of further investigation of the spray parameters on thermal fields inside the sample are: obtaining accurate data about the characteristic points in a coordinate system "time - temperature"; the definition of the geometric parameters of the samples influencing on the rate of cooling; elaboration of the features of the influence of water consumption and processing time on the intensity of the process.

This study was finished in 2012 year.

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