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Investigation of the Water-Air Cooling Process of the Thick-Walled Extruded Profile Made of Alloy En Aw-6060 on the Output Table

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A device has been designed for physically modeling quenching by means of two-phase water-air spray cooling in the line of a horizontal hydraulic extruding press. The influence of the section velocity and the water/air pressure ratio has been investigated using the combinations 5/3, 3/3 and 1/2 bar. The temperature change has been measured in an EN AW6060 alloy profile having a 20×40 mm cross-section during cooling from temperatures of about 550°C. The cross section's temperature reduction was determined prior to entering the workspace of the first pair of nozzles, due to heat transfer along the length of the sample as well as during its translation along the rows of nozzles. The temperature difference between the surface (at a depth of 1/6 of the section thickness) and the longitudinal axis of the section was quantified. This difference increases with reduced profile velocities and decreases with higher pressures of both spray components water and compressed air. For the investigated research conditions, this difference ranges from 6 °C to 60°C. Immediately after a length of the profile's cross-section exits the nozzle zone, a temperature equilibrates over the cross-section: for 0.3 seconds, the temperature gradient in the cross-section is reduced by 5-fold at a surface depth of a 1/3 of the section thickness. The average values of the heat transfer coefficients in the temperature range of 500 °C to 200°C were determined by the equilibrium method. These coefficients can reach up to 21 kW/(m_2K) for a water pressure of 5 bar and an air pressure of 3 bar at cooling rates of 85 K/s. The required mechanical properties were obtained according to the EN 755-2 for all cooling variants having a final profile temperature of more than 350°C.

Keywords: ALUMINUM ALLOY EN AW-6060, TWO-PHASE WATER-AIR SPRAY COOLING, PROFILE TEMPERATURE

Introduction

Text Al-Mg-Si alloy systems occupy the largest part of the range (up to 90%) of modern specialized direct extrusions. Sufficiently higher strength of these alloy's products is obtained by artificial aging after quenching. In order to achieve the T6 condition, quenching of Al-Mg-Si alloys in the line of the extruding press is normal practice; as stated in the EN 755-2. In this case, a better quality of profile surface is obtained compared to quenching in a separate unit.

The main factor affecting the productivity of the line is extrusion speed. On the other hand, this affects extrusion force, which is limited by the press power, and the profile outflow velocity. For massive profiles made of alloy EN AW-6060, the extrusion force is rarely a limiting factor. Outflow velocity in this case is limited by the time which the profile spends in the quenching device and by the cooling rate. Still, it should be considered that most of the profiles made of the EN AW-6060 alloy have complex cross-section geometries, and often possess large differences in wall thicknesses at the perimeter (3 to 6 mm or more). Owing to the risk of warping, these profiles should not be cooled by standing water waves.

The most effective way of quenching profiles with complex cross-sectional shapes is to employ a water-air cooling spray. Its application allows one to adjust the heat transfer coefficient as well as to generate gradient cooling over the cross section and along the profile's length [1].

Cooling rates, required to obtain the specified mechanical properties, vary from 3 to 15 K/s for the 6xxx series alloys up to 50 K/s. The maximum attainable cooling rate with conventional air cooling is 2 to 3 K/s [2].

As shown in work of [3], the change in temperature over the profile's cross section can be computed using the finite element method; for example, program ANSYS®. It is necessary to give the correct heat transfer coefficient, which depends on several factors: the type of nozzle (flat or round), the temperature of surface being cooled down, the distance from the nozzle to the surface, the distance from the cooling point to the nozzle axis, the angle of droplet impingement and also the pressure of air and water, which defines the specific consumption of coolant. The research reported in [4] and others deal with determining such relationships. Using a different formulation, the influence of some of these factors is replaced by another parameter such as the water discharge per unit of time and per unit of surface area [2, 5].

One of the tasks in designing devices for profile cooling is to determine the optimal distance between the nozzles. Reducing the total number of nozzles and increasing the distance between them can cause the problem of profile surface reheating. This reheating is due to the temperature gradient through the profile's volume [1, 2]. For example, in the case of water cooling this, in the opinion of the author [2], is optimal for a distance of 150 mm along the axis of the extrusion.

Modeling the cooling during quenching is also treated in the works of [6, 7]. However, their applicability is limited by using a constant heat transfer coefficient [6], constant pressure of water [7] or by the specific use of the experimental data. The shape distortion of the profile can be predicted by mathematical modeling, as shown in the work of [8].

Despite the considerable opportunities provided by FEM simulations, the correctness and accuracy of the boundary conditions determine the computation's accuracy for the temperature field and the prediction of mechanical properties. Therefore, to verify the numerical solutions, or to obtain the direct dependence of the temperature and cooling rate from the process parameters, the task arises to experimentally determine the temperature field in the extruded profile's cross section.

The purpose of the research is to determine the temperature changes in the body of an extruded rectangular bar of an EN-AW6060 aluminum alloy for a two-phase water-air spray cooling on the extruder's lead-out table.

Methodology

Studies of temperature change over the cross section of the profile, cooled at the extruder's exit, were carried out using a device for spray cooling installed in a detached roller conveyor. This allowed the need for fixing the device to the press line to be eliminated. For this purpose, an installation (**Figure 1**) has been constructed for simulating the cooling in the press line – on the lead-out roller conveyor. The construction of the equipment used here also includes an electric resistance furnace (1) having a forced air circulation. The actual profile temperature deviation is -1/+2 °C. Actually, the water-air cooling installation consists of a frame (3) with two holders (4); each of which has 30 nozzles at a distance of 56 mm from each other. The nozzles are located opposite to each other in the vertical plane. Although the distance from the nozzle exit to the surface of the profile can be adjusted, in this case, it was fixed to 100 mm. The actual water and air pressure deviation was ± 0.05 bar from the nominal values. The nozzles used were produced by SSCO-Spraying Systems AG № SU14 (nozzles for fluid № 2850, for air 73160). The design of the injector is shown in **Figure 2**.

Translation of the sample was performed by a cable, wound onto a drum attached to the motor shaft. The motor is placed at the end of the roller conveyor's section. It is possible to smoothly adjust the rotational velocity within the range of 7 to 84 rpm; this corresponds to a linear sample velocity of 2 to 24 m/min. This range adequately covers the real extrusion speeds of the Al-Mg-Si alloys' profiles.

Experimental studies have been performed using profiles of the EN AW-6060 aluminum alloy having a 20×40 mm rectangular cross-section (**Table 1**).

Table 1. Chemical composition (wt.%) of the EN AW-6060 alloy used in the experiments

Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Zr	Ni	Pb	Bi	Al
0.433	0.195	0.0055	0.011	0.442	0.001	0.0053	0.014	0.0004	0.0042	0.0016	0.0004	rest

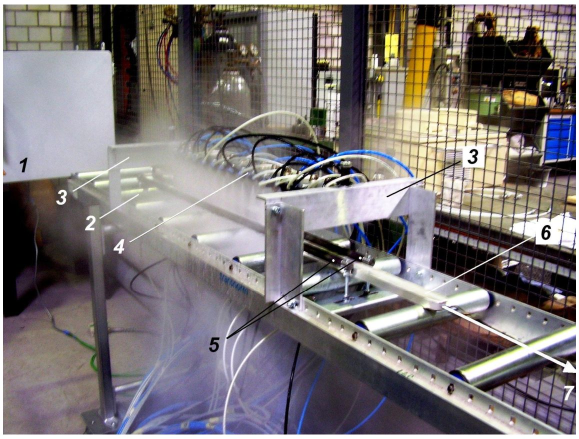

Figure 1. Water-air cooling installation: 1 – furnace; 2 – roller conveyor; 3 – frame; 4 - holder with nozzles; 5 – guides; 6 - sample with installed thermocouples; 7 - motor with the drum (not shown)

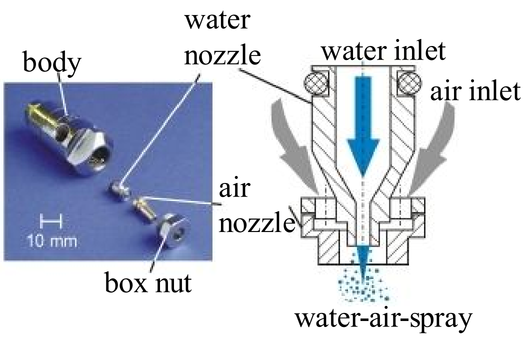

Figure 2. Injector

Temperature measurements were performed using chromel-alumel thermocouples (type K), calked into the profile. The thermocouples have a shell diameter of 0.5 mm. The sampling frequency was 100 Hz. The layout of the thermocouples is shown in **Figure 3**. Three thermocouples were located in the vertical plane of symmetry (20 mm from the edge of the horizontal sample surface) at an equal height – 3.3 mm. That is, a 1/3 of the profile's half height. Thermocouple № 1 was located along the longitudinal axis of symmetry and № 3, closest to the profile's surface. In addition to this, thermocouple № 4 was placed in the same way as № 1, on the horizontal plane of symmetry, but at a distance of 10 mm from the lateral surface (1/4 of the profile's width).

In addition to the measuring the temperature, cooling of the 20×40×500 mm samples was carried out without thermocouples to determine the mechanical properties as a function of temperature.

Thermal treatments in all cases corresponded to T6 mode according to the EN 755-2 - quenching followed by artificial aging. Cooling (in most cases, by quenching) was performed using water-air mixture and, for comparison, immersing in water. Tensile tests were carried out in accordance with EN 10002-1.

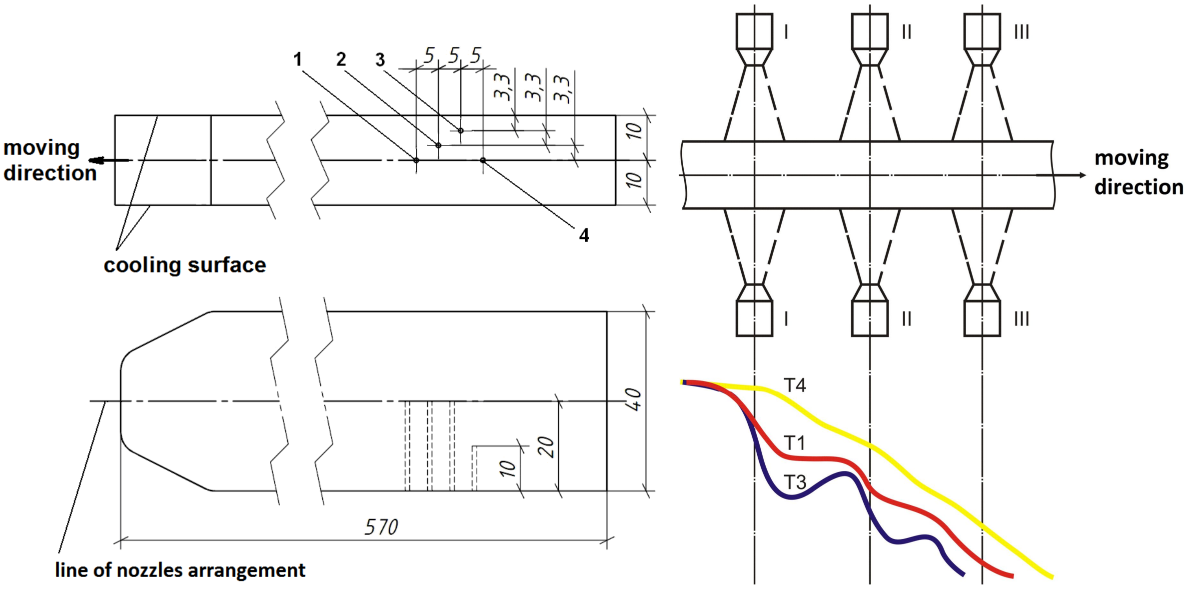

Figure 3. Layout of thermocouples and injectors

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mixture and, for comparison, immersing in water. Tensile tests were carried out in accordance with EN 10002-1.

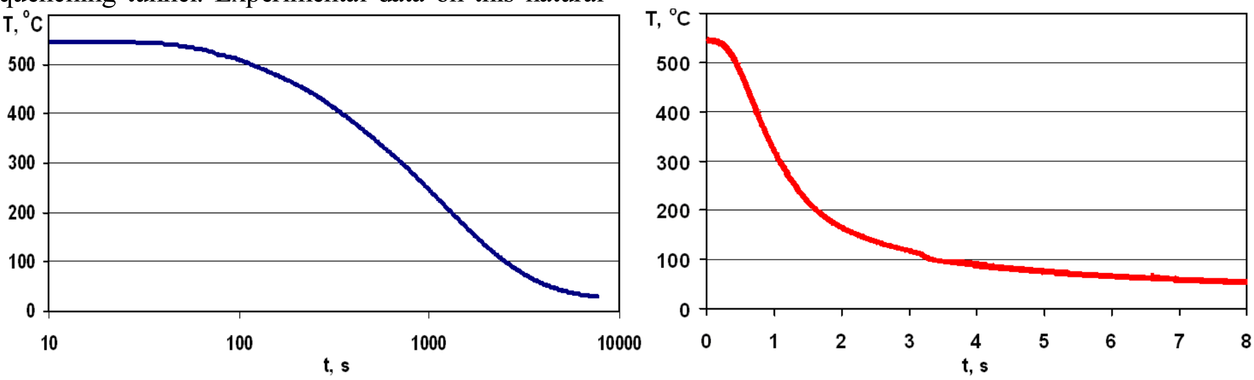
Results and Discussion

To determine the optimal mode of cooling, it is necessary to know how the profile temperature will decrease whilst the profile moves from the die to the quenching tunnel. Experimental data on this natural air cooling for the 20×40 mm profile without the use of additional devices is shown in Figure 4a. In the temperature range 450-550 °C, most critical for quenching, the rate of cooling can be represented in the form of a linear relationship:

$$T = 550 - 0.513 \cdot t,$$

where T – temperature in °C, t – time in s.

Thus, in this case, the cooling rate reached 0.51 °C/s



a b

Figure 4. The change in temperature at the center of the 20 × 40 mm profile's cross section by naturally cooling in air (a) and quenching in water (b)

On quenching in water, the profile cools down to the temperature of 200 °C at the profile's axis in only 1.5 s (**Figure 4b**). This corresponds to a cooling rate of 200 °C/s.

The temperature change during the two-phase cooling modes (**Table 2, Figure 5**) was analyzed for different air and water pressures; that is, W1A2 corresponds to 1 bar water pressure, and 2 bars of air pressure and so on. For the analysis, the following characteristics were used: V – speed of the profile; T_f – temperature on exiting from the furnace (average of readings from four thermocouples); T_a - temperature of the sample on entering the zone of the cooling device; T_1 -T_4 – temperatures in the cooling process according to the readings from thermocouples № 1 to 4; $T_к$ – the final profile temperature.

Table 2. Profile temperature change over the cross section during cooling

Mode	V, m/min	T_a, °C	T_f-T_a, °C	After the first nozzle couple				After the 3rd nozzle couple			$T_к$, °C
				T_1	T_3	T_1-T_3	T_a-T_1	T_1	T_3	T_4	
W1A2	2.5	517	35	486	476	10	31	395	368	434	54
	5	534	12	529	523	6	5	502	495	512	372
W3A3	3	510	34	470	449	21	40	320	284	371	32
	6.5	540	9	494	486	8	46	495	488	508	364
W5A3	3	514	30	408	343	65	106	168	140	178	26
	4.8	530	23	410	348	62	120	246	213	269	38

The temperature of the samples exiting the furnace T_f was 545 to 550 °C. As the profile traverses the pairs of nozzles, the rear part of the sample is being cooled down due to heat transfer along the sample's length. This leads to a reduction in the temperature of the metal entering the working area of the first pair of nozzles. The difference in temperature between T_f and the temperature on entering the zone of active cooling (T_a) was 30 to 35 °C and 9 to 23 °C at speeds of 3 m/min and 6 m/min, respectively (see **Table 2**). The deviations within this range are associated with two factors: 1) temperature fluctuations in the heating furnace and the sample transfer time to the roller conveyor, 2) cooling mode – the more intense it is, the more the metal cools down before entering the active zone. By analyzing the graphs in **Figure 5**, it is possible to take into account the distance between the thermocouples in the longitudinal direction (see **Figure 2**): the cross-section of the profile, which contains every subsequent (by number) thermocouple, will be at the same coordinate along the installation axis in 0.1 s or in 0.05 s at speeds of 3 m/min or 6 m/min, respectively – thus the time delay in this case is relatively small.

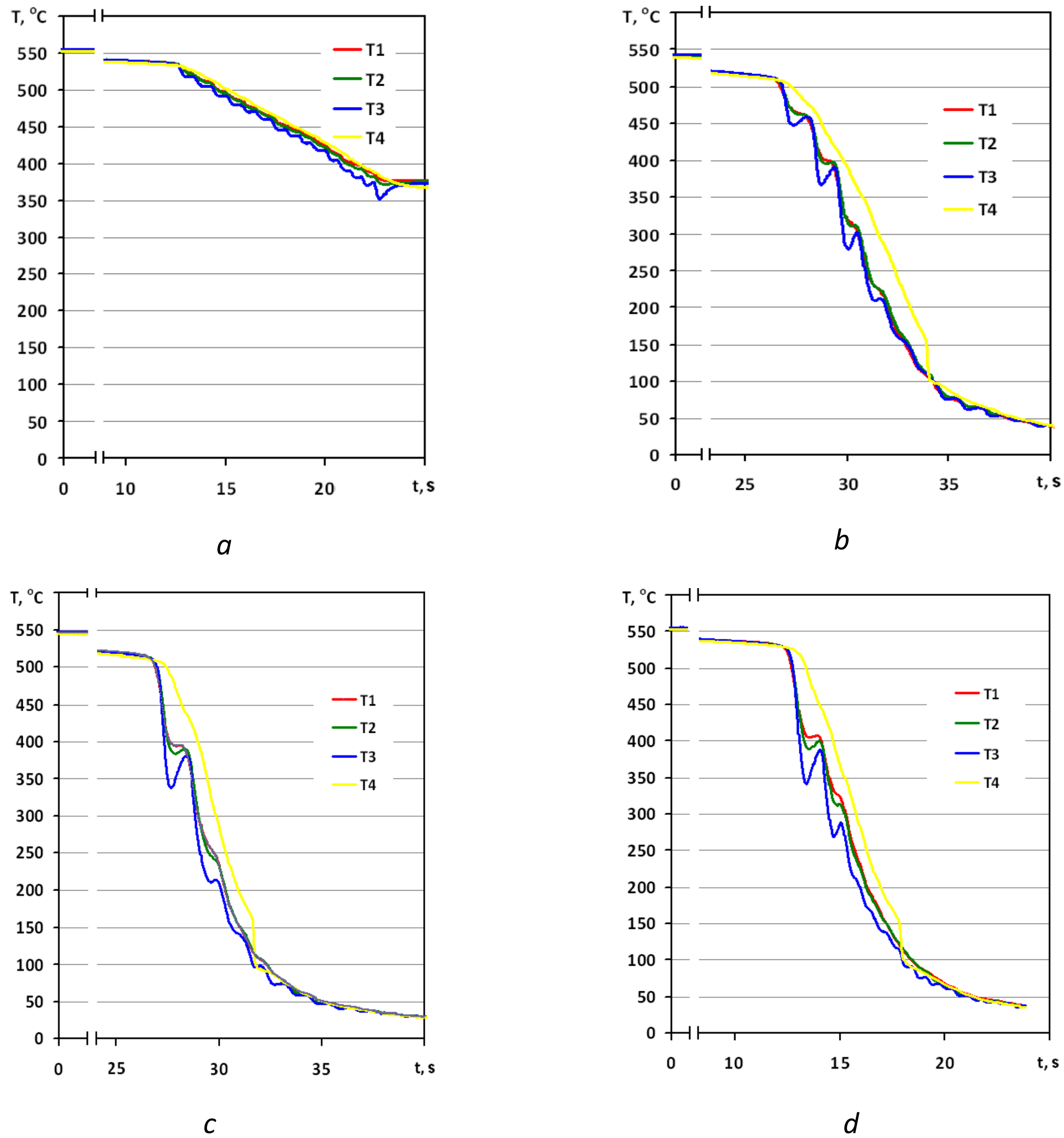


Figure 5. The change in temperature as a function of time using different cooling modes (the numbers in the designations are W_ - water pressure, bar; A_ - air pressure, bar; the last digit is the profile speed, m/min): a – W1A2-6, b – W3A3-3 c – W5A3-3, d – W5A3-6

Acknowledgements

Furthermore, as a profile moves past the first pair of nozzles, the temperature drops – the value (T_a–T_1) reaches 120 °C. This value depends significantly on the air and water pressure. The difference between the readings of the first (on the axis of the profile) and the third (near the surface) thermocouples ranges from 6 to 60 °C, depending on the water-air mixture components' pressures. The largest difference is measured for the W5A3 mode; this mode provides the highest specific discharge of water and, on increasing the speed of the profile, this temperature difference decreases. Immediately after the profile's section leaves the effective area of the nozzle, the cross sectional temperature equilibrates (**Figures 3** and **5**). Due to the residual heat of the inner layers of the metal, the temperature at the surface increases (the peaks are clearly visible on the third thermocouple's readings) and slightly reduces on the axis of the profile. This phenomenon is explained by the non-uniform distribution of water over the surface of the profile – the bulk of water is focused into an area with a diameter of 25-30 mm for an adjacent nozzle interval of 56 mm. Thus, a temperature gradient in the metal reduces by 5 fold at a depth of 7 mm in the cross section over a time period of 0.3 s.

On traversing further between the rows of nozzles, the temperature of the metal continues to reduce but becomes less intense. Also, attention is drawn the temperature profiles of T_1 and T_3. These profiles exhibit a peak in the inactive area between the rows of nozzles. This peak is due to heat transfer from the lateral parts of the profile. Thermocouple number 4 was installed to register this transfer (see **Figure 4**, modes W5A3-6 and W1A2-3). The temperature difference T_4–T_1 can reach 50 °C.

The data analysis (see **Table 2**) shows the benefits of cooling with a maximum pressure and, as a consequence, quantity of supplied water. After the first 3 pairs of nozzles, for the profile speeds studied here, the temperature almost reached the value that eliminates entering the region of incomplete quenching in the TTP-diagram (time-temperature-properties diagram). However, such intensive cooling is not always justified since it leads to a rise in thermal stresses and increases the risk of profile warping. It can be seen from **Figures 5a** and **5b**, and **Table 2**, that a low final profile temperature can also be achieved – no more than 60 °C - at lower profile speeds and water pressures of 3 or even 1 bar.

The cooling time to a temperature of 200 °C was 6 s for W3A3 mode with the speed of 3 m/min, and, for W5A3 mode using different speeds (3 and 6 m/min), was almost the same – about 4 s.

The average cooling rates according to the readings from 4th thermocouple are, within the temperature range from 500 to 200 °C, 85 K/s, 51 and 24 K/s for modes W5A3, W3A3 and W1A2, respectively (**Table 3**). These values were estimated as the average integral of the data presented in **Figure 6**. The presence of waves on the charts is related to the movement of the profile element from one nozzle to another. The significant difference in heat transfer coefficient values is associated with the change in water discharge for changing air and water pressure ratios. Thus the water discharges for one nozzle are 7.9, 3.3 and 0.3 g/s for the modes W5A3, W3A3 and W1A2 described above, respectively [9].

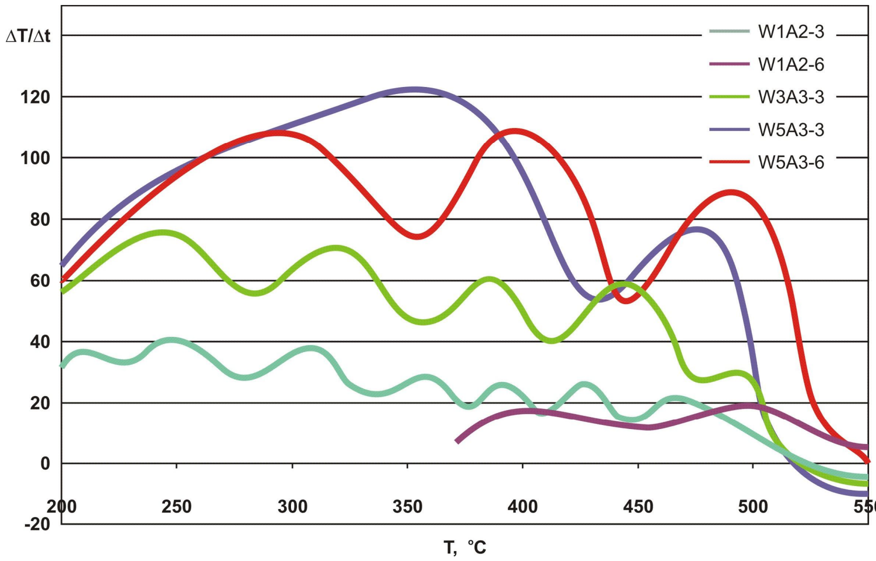


Figure 6. Dependence of cooling rate on temperature using different cooling modes

One can estimate the average heat transfer coefficient by using the equilibrium approach based on data from the 4-th thermocouple, which reflects the average profile temperature. We equate the amount of heat released from the cooling surface (1) to the amount of heat lost by the metal over the determined temperature range from 500 to 200 °C (2).

$$Q = \alpha FSt(Tm–Tc), \qquad (1)$$

$$Q = cm(Tmax–Tmin), \qquad (2)$$

where α – heat transfer coefficient, F_S – the area of the cooling surface, T_m – average metal temperature in the studied range (350 °C), T_c – cooling medium temperature (30 °C), c – heat capacity coefficient, m – mass of metal, T_{max} and T_{min} – the maximum (500 °C) and minimum (200 °C) in the investigated temperature range.

Then the heat transfer coefficient is defined as

$$\alpha = c\rho sb(T_{max}–T_{min})/[2b_c\Delta t(T_m–T_c)], \qquad (3)$$

where s – profile thickness, b – width, Δt - cooling time from temperature T_{max} to T_{min}, b_c – the average equivalent width of the cooling strip on the profile, which is equal to the value of b multiplied by the ratio of cooling area spot to the edge area of the profile with the length equal to the step between the nozzles.

The ratio, $(T_{max}–T_{min})/\Delta t$, is the average cooling rate given in **Table 3**.

Thus, the values of the heat transfer coefficients for various cooling modes significantly differ and are approximately 21, 12.6 and 6 kW/(m^{2}K) for the modes W5A3, W3A3 and W1A2 respectively. By introducing the parameter γ, which describes the quantity of water impingeing on 1 m^2 of a cooled profile surface, it is possible to estimate the amount of water needed for quenching. This quantity is characterized by the parameter Ω – the ratio of water mass to the profile mass (see **Table 3**). The required Ω value for the conditions considered here is about 0.2. However, it should be remembered that this parameter does not take into account the ratio of the mixed components' pressure, which determines the distribution of water on the surface and the droplet's speed and specifies how the steam jacket is split on the profile.

Using the heat transfer with variable intensity by means of changing the water-air jet's parameters in an industrial environment will allow the complex configuration profile element's cooling rate to be adjusted.

Table 3. The average cooling rate and the heat transfer coefficient

Mode	Δt s	$\Delta T/\Delta t$ K/s	T_0 °C	T_c °C	α W/(m^{2}K)	γ кg/m^2	Ω кg/кg
W1A2-3	12.4	24.0	500	200	5900	2	0.02
W1A2-6	8.3	15.1	500	375	3720	1	0.01
W3A3-3	5.8	51.4	500	200	12660	17	0.24
W3A3-6	4.3	31.6	500	375	7200	8	0.12
W5A3-3	3.5	85.5	500	200	21000	40	0.59
W5A3-6	3.6	84.3	500	200	20770	20	0.29

Data on how the final cooling temperature affects the mechanical properties at different modes is summarized in **Figure 7.** With a final profile temperature $T_к$ = 300-350 °C, conventional yield stress decreases by 30-50% in comparison with $T_к \approx 200$ °C. Also, water quenching and water-air cooling to $T_к \approx 50$°C result in slightly lower strength values in comparison with $T_к \approx 200$°C. This can be explained by the aging process beginning at a temperature of about 200°C.

The required mechanical properties have been obtained according to the EN 755-2 for all cooling modes, except for $T_к$=356°C (mode W1A2-6, **Table 3**): minimum ultimate strength of 190 MPa, conventional yield stress of 150 MPa and elongation of at least 12%.

Conclusions

1. A detached two-phase water-air spray cooling device for quench simulations in the line of a horizontal hydraulic extruding press was put into operation. The temperature change has been determined over the 20×40 mm profile cross section of an EN AW6060 alloy during cooling from temperatures of 545 °C and 550 °C.

2. The profile temperature is reduced on entering the working area of the first pair of nozzles because of the heat transfer along the sample to the already cooled profile volume. The

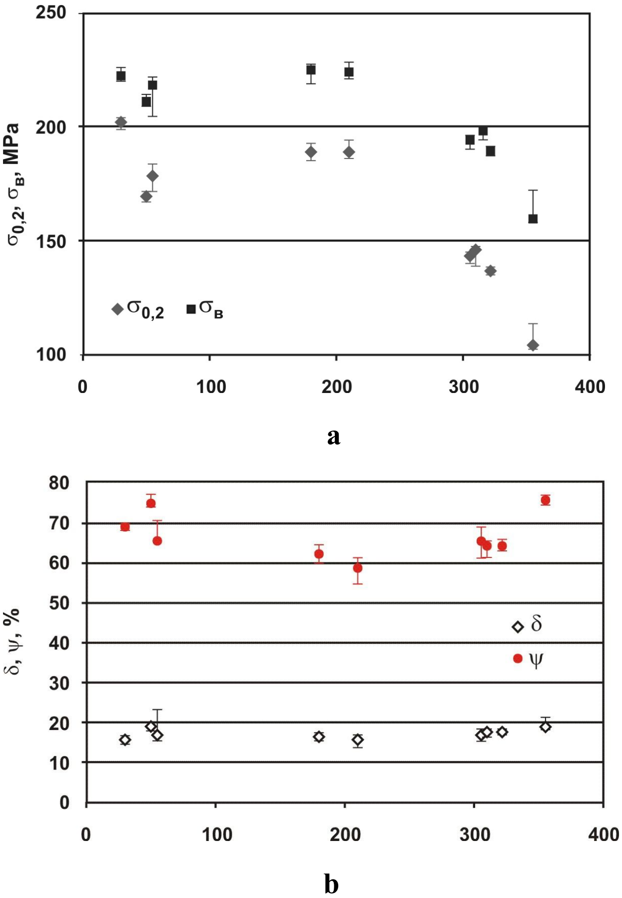


Figure 7. Strength (a) and plasticity (b) characteristics in relation to temperature of the final cooling

difference between heating temperature and the temperature when entering the active zone is 30 °C to 35 °C.

3. On entering the zone of active air-water spray cooling by reaching the first pair of nozzles, the temperature drops by about 120 °C. On proceeding to the next nozzle position, the intensity of cooling decreases as the sample approaches the device's exit and depends on the pressure of the mixed components (usually decreases as the pressure is lowered).

4. The difference between the temperature of the surface (at a distance of 1/6 profile thickness) and the profile axis ranges from 6 °C to 60 °C for the studied conditions and increases with reduced velocities or an increase in the pressure of the water-air mixture. The profile temperature along the axis is lower than that at a distance of one quarter the profile width because of the uneven water distribution on the profile's surface (the bulk of the water reaches an area with a diameter of 25 mm to 30 mm).

5. After the studied profile's cross-section leaves the nozzle area, temperatures equilibrate over the cross section; the surface temperature increases due to heat transfer from the metal's interior whereas the temperature close to the profile's axis is slightly reduced. The profile's temperature gradient decreases by 5 fold at a depth of 7 mm in the cross section within a time of 0.3 s.

6. Heat transfer coefficients in the temperature range of 500 °C to 200 °C have been determined using the equilibrium approach. These coefficients vary significantly for different cooling modes. At a water pressure of 5 bar and an air pressure of 3 bar, the heat transfer coefficient may reach up to 21 kW/(m^2·K) while the cooling rate amounts to 85 K/s.

7. Increasing the final temperature of the profile Tк from 200°C to 300 °C and to 350°C decreases the yield stress by 30% to 50%, although reducing $T_к$ to 30°C lowers the strength. This reduction may be related to starting the aging process at temperatures of about 200°C. The obtained dependencies can be used to predict the mechanical properties of the EN AW-6060 alloy following a T6 mode of heat treatment (quenching with subsequent artificial aging) when using a water-air spray cooling.

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Исследование процесса водовоздушного охлаждения толстостенного прессованного профиля из сплава EN AW-6060 на выходном столе

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Разработана установка для физического моделирования закалки в линии горизонтального гидравлического пресса путем двухфазного водовоздушного охлаждения. Исследовано влияние скорости перемещения профиля и соотношения давлений воды и воздуха в комбинации 5/3, 3/3 и 1/2 бар соответственно. Определено изменение температуры по сечению профиля 20×40 мм из сплава EN AW6060 при охлаждении с температур около 550 °С. Установлена величина снижения температуры профиля перед входом в рабочую область первой пары сопел за счет теплопередачи по длине образца, а также по мере продвижения вдоль рядов сопел. Показано, что разница между температурой у поверхности (на расстоянии 1/6 толщины профиля) и на оси профиля увеличивается при снижении его скорости либо увеличении давления компонентов водовоздушной смеси; эта разница составляет для исследуемых условий от 6 до 60 °С. Сразу после выхода некоторого сечения профиля из зоны действия сопла температура по сечению выравнивается: на расстоянии от поверхности, равном 1/3 толщины профиля, за время порядка 0,3 с градиент температур в его поперечном сечении уменьшается в 5 раз. В диапазоне 500...200°С путем обратного пересчета определены средние значения коэффициента теплоотдачи. Этот коэффициент при давлении воды 5 бар и воздух 3 бар может достигать 21 кВт/(м^{2}К), а скорость охлаждения – 85 К/с. Во всех вариантах охлаждения, кроме температуры конца охлаждения более 350°С, получены требуемые по EN 755-2 механические свойства.