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Extrusion and Air-Water Cooling of Al Si1MgMn Alloy Extruded Profiles

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Temperature of EN-AW 6082 alloy solid profiles and pipes after extrusion and cooling as well as their mechanical properties at various regimes of heat treatment are defined at JSC “Dniprovskiy Factory “ALUMASH”. Effect of cooling conditions on temperature change of extruded articles and also on their mechanical properties is determined; comparison to EN 755-2 requirements is carried out. Results are obtained at close cooperation of Metal Forming Department of National Metallurgical Academy of Ukraine, JSC “Dniprovskiy Factory “ALUMASH” (Ukraine) and Forschergruppe 922 “Strangpressen” (Germany).

Keywords: EXTRUSION, COOLING, HARDENING, MECHANICAL PROPERTIES, ALUMINUM ALLOY ALSI1MGMN

Introduction

Al-Mg-Si alloys are widely applied in construction and engineering industry. In particular, alloys 6060 and 6063 (according to EN 573-3) are the most widespread in manufacture of building envelopes. However requirements to strength of elements at their mass conservation grow. In this relation, alloys with higher strength - 6082, 6061, 5251 are expected to be more widespread. Alloy EN AW-6082 (Al Si1MgMn) is one of the strongest alloys of system Al-Mg-Si that is featured by high processibillity at extrusion, corrosion resistance, and also possibility to produce profiles with high quality surface. Possibilities to manufacture products from alloy 6082 with target level of mechanical properties by means of extrusion with hardening on a press and subsequent aging treatment are studied in present research.

Effect of chemical composition on properties and quality of Al-Mg-Si alloy profiles is covered in the literature enough, so we will not discuss this issue further. We will only note that increase of content of Mg, Si, Mn and Cr leads to alloy hardening. Disperse intermetallic phases $A1_6Mn$, α (A1-Si-Mn), $A1_7Cr$ promote development of press-effect which is expressed in conservation of nonrecrystallized structure in products after hardening and aging treatment [1].

The major factors that enable to have an effect on quality of profiles are temperature-speed parameters of extrusion, method and regime of heat treatment.

Interrelations of extrusion regimes and quality of 6082 alloy extruded products are covered in works [1, 2, etc.]. Data of many authors about optimum combination of temperatures and extrusion speed can essentially vary even at equal values of elongation ratio. Limitative parameters are pressing force (or stress on a pressing disk), defects of profile surface, depth of occurence of coarse-grain zone, required strength, etc.

According to data [2], the highest mechanical properties are achieved at cooling rate more than 500 °C/min. According to [1], profiles should be cooled to 200 °C at the rate > 6 °C/s. In work [3] it is pointed out that specified alloy should be cooled from 530-560 ºC to 150 ºC for 25-180 seconds, i.e. cooling rate is from 3 to 15 ºC/s. Differences in the values resulted above can be explained by different chemical composition of investigated alloys and temperature range for which value of cooling rate is specified. Critical cooling rate should be defined by tangent slope to C-curve of breakdown of solid overcooled solution or to the so-called TTP-diagram (time-temperature-properties). Detailed information about diagrams of isothermal decomposition of solution in aluminum alloys is available in [4], for alloys 6082 and 6063 in work [5].

It is easier to provide high cooling rate when hardening on certain plants. However, products quenched on a press have a light brilliant surface unlike semimanufactured materials with dark oxidized surface quenched after heating in air furnaces [6]. The second important advantage of hardening in a press line is a possibility to control temperature of certain elements of profile cross-section in order to avoid warpage. For this purpose Balanced Intensive Cooling System BICS [3] is implemented when the charge of cooling air-water mix or air is adjusted from each side of the profile. However, for effective operation of such plants, especially when cooling thick-walled profiles, it is necessary to decrease extrusion speeds and increase length of the plant. And information about effect of extrusion regime on profile temperature before hardening, effect of cooling conditions on temperature of profile element at a time is required.

Modeling of cooling during hardening for achievement of target strength level is considered in work [7]. Mathematical model is developed for alloy 6082 with varied content of silicon, and interrelation between cooling parameters and strength indices is determined. Area between 400 ºC and 300 ºC is a critical range in which cooling rate should be maximum. It proves to be true by data [5] - 300-350 ºC. The model can be used in practice, however the constant value of heat-transfer rate is used in it, and it depends on many factors. In work [8] mechanical properties of profile are forecasted based on modeling of cooling process taking into account nonlinear dependence of air-water cooling rate on temperature of product surface. However, data are obtained for constant value of water pressure, and experiments are carried out for alloy 2024. Work [9] is devoted to modeling of cooling process and forecasting of profile strength – dependence of temperature change in time obtained from experiment on cooling 6061 alloy cylinder with diameter 101 mm which applies certain restrictions on possibility of its usage.

Production of profiles with gradient of properties along the length is of interest. This is can be achieved with application of air-water cooling [10]. Obtained results have restricted application because of low cooling temperatures - from 400 to 500 ºC. Thus, air-water cooling process is perspective in view of profile hardening which provides the minimum warpage and high quality of profile surface.

The task of presented research is to determine effect of parameters of extrusion and cooling processes on mechanical properties of 6082 alloy profiles. Interrelation between temperature-speed parameters of extrusion and properties of profiles is investigated in the first part of work carried at JSC "Dniprovskiy Factory "ALUMASH" (Dnipropetrovsk). Temperature change of products during extrusion and air-water cooling as well as effect of cooling period on mechanical properties are considered in the second part of work – investigations are carried out in Leibniz Universitaet Hannover.

Results and Discussion

Extrusion and heat treatment of profiles at JSC "Dniprovskiy Factory "ALUMASH"

Pressed scrap with corresponding rich alloys was used at foundry floor of the plant. Homogenization at 585 ºC took place after pouring. Chemical composition of metal used further in the experiments is presented in **Table 1**.

The content of basic alloying elements (Si, Mg, Mn) is below the average level (as required by the standard).

Two solid profiles with almost constant wall thickness across the section (2 and 4 mm) and heavy-walled tube (∅ 37 × 5.5 mm) were investigated (**Figure 1 a-c**). The key characteristics of profiles and tubular billet are presented in **Table 2**.

Extrusion was carried out on a horizontal hydraulic press with force 13.5 MN. The maximum pressure on the pressing disk is 680 MPa for this press. Extrusion speed varied in the range 7-10 mm/s for various types of profiles. The temperature of furnace heating was 480-490 ºC. Profile was cooled only in the tunnel of air-water cooling or with water cooling behind the tunnel.

After hardening profiles were cooled down to 20-50 ºC, subjected to stretch flattening with percentage elongation 0.5 %, except for case with additional cooling (1.0 %). Cutting and aging treatment were carried out further. Artificial ageing regime: temperature 85 ºC; time 6 hours. Break between hardening and ageing was 6 hours. In case of natural ageing break between hardening and testing was 5 weeks.

Mechanical properties of profile metal, for which tests were carried out, and corresponding parameters of extrusion are presented in **Table 3**. Tests were conducted on flat samples for a channel bar (cut out from the middle of wall) and L-bar, and on segmentary samples - for pipe.

Table 1. Chemical composition of alloys used in the experiments

Alloy	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ni	Al
EN AW-6082 (EN 573-3)	1.7-1.3	<0.5	<0.1	0.4-1.0	0.6-1.2	<0.25	<0.2	<0.005	rest
6082 (IW)	0.73	0.22	0.05	0.48	0.61	0.003	0.009	0.003	rest
6082 (ALUMASH)	0.82	0.22	0.003	0.47	0.69	0.004	0.024	0.003	rest

Table 2. Characteristics of profiles and tubular billet (diameter 152 mm)

No.	Type	s, mm	F_1, mm^2	n	μ	μ_{def}	L_0, mm	L_1, m
21176	U	4	436	1	41.6	45.5	460	11.6
11002	L	2	76	3	79.5	87.0	520	22.3
12217	O	5.5	544	1	33.3	36.5	625	9.3

* s - wall thickness; F_1 - sectional area; n - number of threads; μ - elongation ratio; L_0 - length of tubular billet; L_1 - nominal length of profile, m

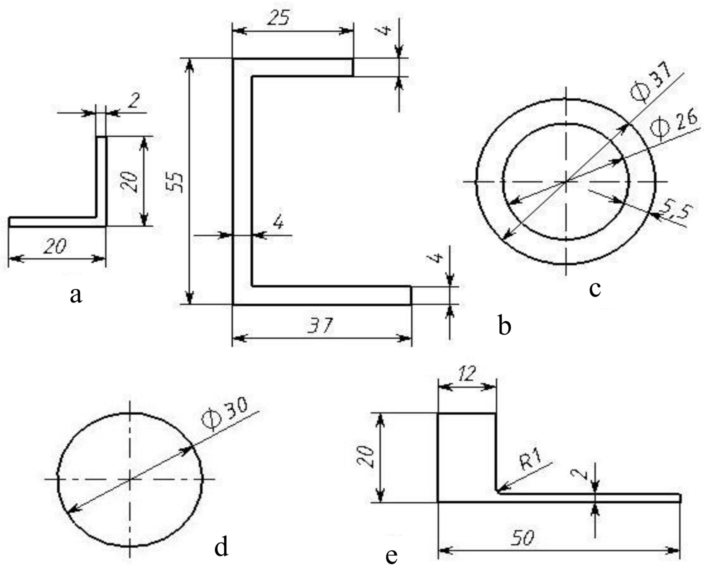
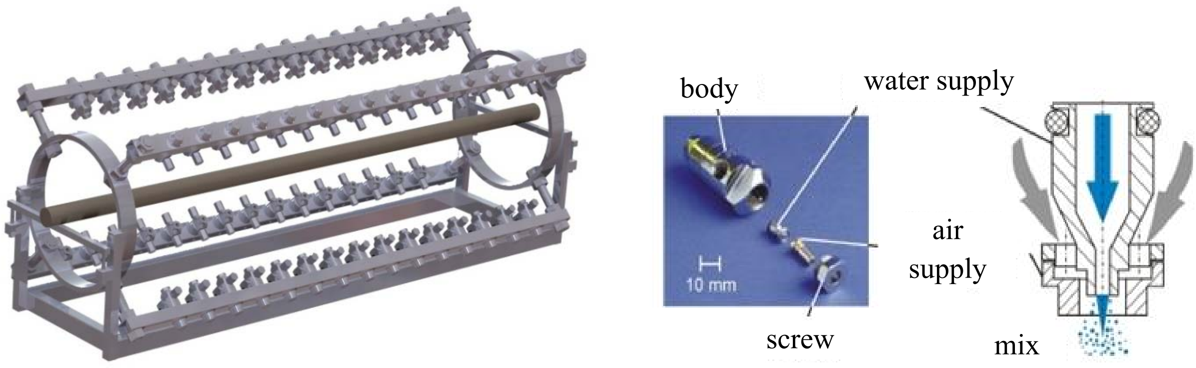


Figure 1. Drawings of extruded products: *a* – channel bar 21176; *b* – L-bar 11002; *c* – pipe 12217; *d*– rod; *e* – non-equilateral angle



a b

Figure 2. Installation diagram of air-water cooling (*a*) and nozzle (*b*)

Table 3. Extrusion and heat treatment regimes, results of mechanical tests

Grade	*s*, mm	*V*, mm/s	*W*, m/min	Cooling	p_{max}, bar	T_{pr}, °C	T_{cool}, °C	Ageing type	$\sigma_в$, MPa	$\sigma_{0,2}$, MPa	δ_5, %
U1E	4	8	20.0	T	181	525	497	natural	220	104	18.9
U1И	4	8	20.0	T	181	525	495	artificial	245	196	11.3
U3И	4	8	20.0	T+W	173	525	404	artificial	231	204	10.6
L22И	2	7	33.4	T	178	500	377	artificial	306	254	8.8
O1И	5.5	10	20.0	T	212	545	526	artificial	273	214	10.0

$*V$ - speed of ram; *W* - profile extrusion speed; cooling type - T - only in the tunnel; T+W - with additional water supply before the tunnel; p_{max} - maximum pressure in the basic cylinder of press (limiting value 270 bar); T_{pr} - temperature of profile surface between front cross-member and tunnel; T_{cool} - after cooling; $\sigma_в$ - ultimate tension; $\sigma_{0,2}$ - conventional yield strength; δ_5 - percentage elongation

Analysis of results showed that in all cases pressure in the press system did not exceed maximum, i.e. predetermined speed of ram was always achieved. Pressures at extrusion of all extruded products were at the level characteristic for alloy 6060. Extrusion with speeds exceeding values specified in **Table 3** is not reasonable because of appearance of strips and edge fins on the profile surface. Ripple markings appear in the weld seam zone at extrusion speed 24 m/min, at further increase of speed these ripple markings become cracks.

Profiles with thicker wall have higher temperature at the entry in tunnel that is related to more absolute heating capacity of profile. Besides, pipe metal is more heated due to a flowage in the bridge die. More thick-walled profile is also worse cooled by air-water mix. However, the major cause of profile high temperature at the exit from tunnel is its small efficiency because of fixed lay-out of nozzles in tunnel walls. Therefore, channel bar and pipe have no time to cool to recommended [3] temperature 150 ºC during maximum 180 seconds. $\sigma_в$ value corresponding to condition T6 is achieved only on the L-bar with wall thickness 2 mm. Achievement of target strength level on the pipe unlike channel bar is explained by higher (on 20 ºC) temperature of the product before hardening. For all products, and especially L-bar, air blasts play a positive role for air cooling after tunnel.

Besides, experimental extrusion of alloys 6061 and 6005 was carried out by regimes specified above. Though their detailed analysis is beyond the scope of this work, comparison to results obtained for alloy 6082 is of interest. Dependence of mechanical properties on wall thickness, cooling period, hardening temperatures and other factors is similar for all three alloys. During extrusion of any investigated alloy profiles 2 mm thick without additional cooling $\sigma_в$ = 300 MPa, however target value $\sigma_{0,2}$ according to T6 is not achieved.

Additional water cooling of channel bar for all three alloys led to minor change of properties. So, for alloy 6082: ultimate strength decreased by 6 %, yield stress raised by 4 %, and percentage elongation dropped by 0.7 % in absolute units. It is obviously related to irregularity of cooling and residual stresses. Water flow is small to ensure the correct cooling rate.

Natural ageing for all three alloys ensures $\sigma_в$ = 205 MPa and σ_5 = 18-19 % (205 MPa and 14 % respectively are required according to EN 755-2).

Thus, extrusion of profiles and pipes with elongation ratio to 80 and 20-30 m/min is not problematic in view of pressing force, weld seam quality and surface defects.

Cooling process and its effect on mechanical properties of extruded products are investigated at Leibniz Universitaet Hannover in order to improve quality of profiles. The major task is to define effect of air-water mix parameters on cooling rate and quality of aluminum alloy EN-AW6082 extruded products.

Rod ∅ 30 mm and unequal L-bar 12×20 and 2×38 mm (**Figure 1 d, e**) were extruded products under investigation. Chemical composition of 6082 alloy homogenized billet is presented in **Table 1**. Extrusion was carried out on horizontal hydraulic press with force 10 MN. Diameter of container - 125 mm, billet - 120 mm. Elongation ratio for L-bar - 38.8, for rod - 17.4.

L-bar was extruded at various temperature-speed regimes to estimate deformation heating-up and cooling rate of profile. Billet was heated in resistance furnace at 470 or 490 ºC, extrusion speed was 10 or 20 m/min. Extrusion was carried out in 15-20 seconds after heating. Container temperature was 40 ºC less than billet temperature. Temperature of profile surface was measured by contact thermocouple NiCr/N (type K).

The following dependences for definition of L-bar temperature with leg thickness 2 mm (T_2) and 12 mm (T_{12}) are obtained as a result of approximation of results:

$$T_{12} = -147.5 + 1.35 \cdot T_b + 5.2 \cdot W - 0.01 \cdot T_b \cdot W; \quad \text{(Eq. 1)}$$

$$T_2 = 270 + 0.5 \cdot T_b - 1.75 \cdot W + 0.005 \cdot T_b \cdot W, \quad \text{(Eq. 2)}$$

where T_b - billet heating temperature, ºC; W - extrusion speed, m/min.

Temperature drop of extruded product surface as it moves to cooling device can be presented by equation 3:

$$T = T_0 - kt \cdot t, \quad \text{(Eq. 3)}$$

where T and T_0 - current and initial temperatures (ºC), respectively; t - time, s; k_t - factor 0.8 for rod ∅30 mm, for L-bar with wall thickness 2 and 12 mm – 1.58 and 1.15, respectively.

Air-water cooling device was developed for experiments on profile cooling (both stationary and during extrusion) (**Figure 3a**). Desired level of water pressure is ensured by compressed air pressure in bottles with water. It is possible to control pressure of water and air with accuracy to 0.1 bar and also process time. Step cooling is also possible. We used nozzles produced by SSCO-Spraying Systems AG №SU14 (nozzle for liquid No. 2850, for air No. 73320). Design and physical configuration of nozzle are illustrated in **Figure 3b**.

Water rate at various combinations of water and air pressure was defined by measuring volume of water V_W flowing from one nozzle per unit time (g/s). Approximation of results allowed the following equation:

$$V_W = a \cdot p_W^m,$$
$$a = -0.033 \ln p_A + 0.043, \quad \text{(Eq. 4)}$$
$$m = 0.3905 p_A + 0.2174$$

where a and m - factors depending on air pressure; p_W - water pressure, bar; p_A - air pressure, bar.

We will analyze change of profile temperature in time at various cooling conditions. The extruded product was fixed in the unit, so distance from the nozzle to surface was 100 mm. Heating temperature was 540+7 ºC.

Measurements were taken by means of thermocouples on one side of extruded article:

1) in the rod ∅30 mm at a depth of 15 mm (i.e. to rod axis);

2) in thick leg of L-bar to the gravity centre of its cross-section (i.e. at a depth of 10 mm on the long side and 6 mm on the short one).

The cooling period to certain temperature at various cooling conditions is presented in **Table 4**.

So regime with pressure of water 5 bar and air 3 bar is optimum in view of the maximum cooling rate. Increase of air pressure to 5 bar at the same water pressure leads to reduction of cooling period by 10 %, however air-flow rate grows. It is not rational to raise air pressure above water pressure at various levels of water pressure since the cooling period increases. Comparing cooling period for regime W5A3 it is clear that for leg of L-bar it is 30 % lower than for rod but not proportional to distance from the centre to nearest surface. This is related to effect of two factors: 1) lay-out of nozzle axes; 2) great ratio of perimeter to sectional area L-bar leg.

When using only air (regime W0A5) the cooling period essentially increases (**Figure 4**), and the pattern of dependence *T* (*t*) changes - the curve is concave, there is no inflection. Typical pattern of cooling rate change over the time is shown in **Figure 5**.

Results of mechanical tensile tests according to EN 10005 of rod ∅30 mm and non-equilateral L-bar subjected to heat treatment by various regimes are presented in **Tables 5, 6**. In all variations presented below initial temperature of heating was 540 ºC for 60-90 minutes for L-bar and 90-120 minutes for rod. After hardening we carried out aging treatment by regime 180 ºC, 4 hours in resistance furnace with air forced circulation. Except for air-water hardening we also conducted water hardening (options 1, 2 in **Table 5** and 1 in **Table 6**), including after intermediate cooling and soaking for 30 minutes at 490 ºC.

Analysis of table data showed that as expected water hardening from temperature 540 ºC ensured maximum strength of all samples. Despite a preliminary soaking at 540 ºC, hardening from temperature 490 ºC led to end option - $\sigma_в$ =310 MPa and $\sigma_{0,2}$ = 260 MPa are required for rod according to T6; however, the authors [3] obtained even smaller value $\sigma_в$ = 270 MPa at similar regime.

As to spray cooling, even regime W5A3 did not enable to achieve target properties for the rod. There are no requirements to condition T5 in EN 755-2, and press hardening is allowed according to T6.

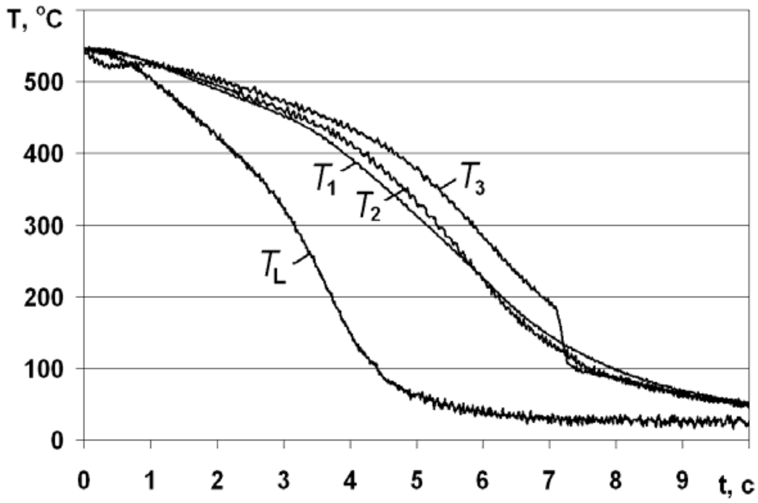


Figure 3. Dependence of extruded article temperature on cooling period, regime W5A3 (pressure of water 5 bar, air 3 bar): on rod axis ∅30 mm: T_1 - on nozzle axis; T_2 - on distance of ¼ nozzle step; T_3 - on distance of ½ nozzle step; T_L - in the centre of thick leg (12 mm)

Table 4. Cooling time *t* (s) to temperature *T* at various combinations of water pressure W and air A (bar) , maximum cooling rate Θ_{max}

T, °C	Rod ∅30 mm							L-bar (*s* = 12 mm)		
	W5A5	W5A4	W5A3	W3A5	W3A3	W3A1	W0A5	W5A3	W1A3	W0A5
400	2.9	3.1	3.3	3.9	3.7	3.4	21	2.2	7.3	8
300	4.0	4.2	4.4	5.4	4.9	4.9	40	3.1	12.6	17
200	4.8	5.1	5.5	7.0	5.9	6.0	66	3.7	15.4	27
100	6.5	6.8	7.2	8.9	7.6	7.5	–	4.0	18.5	47
Θ_{max},°C/s	110	115	120	80	70	95	7	270	60	12

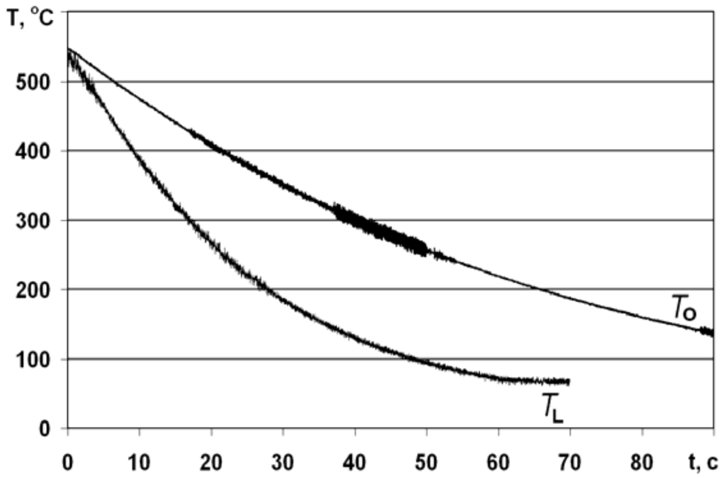


Figure 4. Dependence of rod (T_O) and L-bar (T_L) temperature on air cooling period, regime W0A5

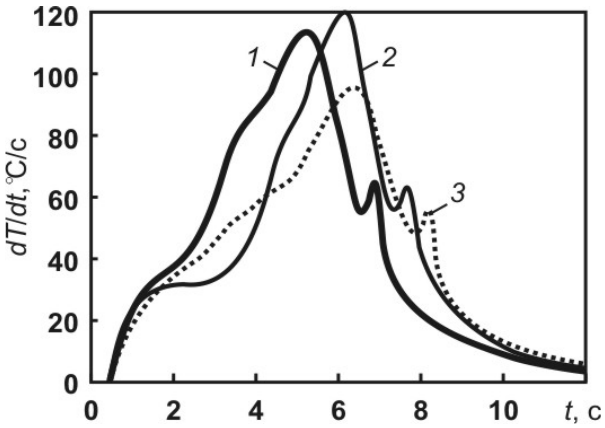


Figure 5. Variation of cooling rate in time at various regimes: *1* – W5A4; *2* – W5A3; *3* – W3A1

Table 5. Mechanical properties of rod metal

No.	Regime	$\sigma_в$, MPa	$\sigma_{0.2}$, MPa	δ_5, %	Ψ, %
1	540 °C – water hardening	362	347	11.9	54.6
2	540-490 °C – water hardening	309	272	13.7	57.7
3	540 °C – W5A3	275	262	16.8	57.3
4	requirements EN 755-2, T6	310	260	8	–

Table 6. Mechanical properties of non-equilateral L-bar metal

No.	Regime	L-bar leg 12 mm thick				L-bar leg 2 mm thick		
		$\sigma_в$, MPa	$\sigma_{0.2}$, MPa	δ_5, %	Ψ, %	$\sigma_в$, MPa	$\sigma_{0.2}$, MPa	δ_5, %
1	water hardening	302	284	13.9	53.8	322	311	11.2
2	W5A3	297	274	15.4	52.8	323	311	11.4
3	W1A3	284	263	15.7	53.1	317	302	10.0
4	W0A5	282	258	15.9	49.5	311	292	10.9
5	EN 755-2, T5	–	–	–	–	270	230	8
6	EN 755-2, T6	310	260	10	–	290	250	8

Values $\sigma_в$ = 270 MPa and $\sigma_{0.2}$ = 230 MPa required by T5 are easily achieved for L-bar at air-water cooling by various regimes. T6 requirements are more rigid, target value $\sigma_в$ was not achieved for leg 12 mm thick, and for leg 2 mm thick - opposite - target strength was achieved by all regimes, even at air cooling (W0A5).

It is necessary to note that at water hardening and air-water cooling by various regimes the target percentage elongation is achieved for both L-bar and rod.

Conclusions

Literature data about effect of key parameters of extrusion process and cooling on mechanical properties of Al-Mg-Si alloy profiles are analyzed.

Temperature of EN-AW 6082 alloy solid profiles (2 and 4 mm thick) and pipes (37×5.5 mm) after extrusion and cooling and their mechanical properties are determined at various regimes of heat treatment at JSC “Dniprovskiy Factory “ALUMASH”.

Dependences of EN-AW 6082 alloy L-bar temperature with legs 2 and 12 mm thick at the exit from press with force 10 MN (Leibniz Universitaet Hannover) on temperature-speed parameters of process as well as temperature of product surface are obtained. Air-water cooling device is developed and fabricated. Water flow at various regimes of spraying (combinations of water and air pressure) is determined.

Effect of cooling conditions on temperature change for L-bar leg and rod, including depending on distance to nozzle axis in direction of rod axis, is determined. It is established that spraying at pressure of water 5 bar and air 3 bar is optimum in view of achievement of maximum cooling rate. Effect of cooling conditions on mechanical properties of specified products is defined, and comparison to EN 755-2 requirements is carried out.

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Прессование и водовоздушное охлаждение прессованных профилей из сплава Al Si1MgMn

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В условиях прессовой линии ОАО «Днепровский завод «АЛЮМАШ» определена температура сплошных профилей и труб из сплава EN-AW 6082 после прессования и охлаждения, а также их механические свойства при различных режимах термической обработки. Определено влияние режимов охлаждения на изменение температуры пресс-изделий, а также на их механические свойства; проведено сравнение с требованиями EN 755-2. Результаты получены при сотрудничестве кафедры ОМД НМетАУ, ОАО «Днепровский завод «АЛЮМАШ» (Украина) и Forschergruppe 922 «Strangpressen» (ФРГ).