Designing and continuous extrusion forming of Al-Mg-Si contact lines for electric railway

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The experimental work aimed to obtaining the aluminum alloy contact lines for trams or light rail. For this purpose was elaborated AlMgSi0.5 Aluminum alloy was elaborated and semi-continuous casted into rods of ϕ 175 x 6000 mm, and then homogenized (520° C / for 16 hours) for the continuous extrusion process. A chamber extrusion die was designed and executed. After continuous extrusion forming, the obtained contact wire has been heat treated (quenching and artificial aging at 155 °C for 14 hours, air cooling). The product was microstructurally analyzed and mechanically tested (Tensile strength, R_m, Elongation, A, Brinell Hardness , HB and tensile forces in the contact wire, F. Results have shown that, although the minimum tensile strength is less than 200 MPa (R_m = 163-248 MPa), the value of total tensile forces F = 4250-6450 kilogram-force (kgf) in AlMgSi0.5 contact wire is superior to the copper wire, (F=3500Kgf according with PN-64/E-90090 standardization and Romanian standard STAS 686-71).

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1. Introduction

Since the early 1960's, the overhead contact lines of electric railways have been studied for continuous improving of specific characteristics (high conducting , low specific resistance, high tensile strength, low specific gravity, low cost, etc) [1-5] and to satisfy the environmental requirements (Electric and Magnetic Field, atmospheric conditions, terrain characteristics, etc), for good exploitation of rail vehicles [6, 7].

Researchers have shown that transmission and distribution of powers, respectively the reliability of energy supply for train/ tramway depends on the quality of interaction between contact line and pantographs [8, 9].

The contact line on electric railway traction is made by longitudinal suspension or catenaries suspension composed of contact wire (nominal section aria of 50-600mm^2), sustained by a massager cable through dropper [5, 10].

In Romania, the contact lines for electric railway can be round or profiled section and are made from electrolytic copper or copper with cadmium, and have sections of 85 mm^2, 100 mm^2 and 150 mm^2, depending on the jobsite [4]. The minimum tensile strength is between 36.2-34.3 daN/mm^2 and elongation A_{10} has a minimum value of 3.5% in all cases [4]. The contact suspension consists of contact wire and supports. The first model of rigid catenaries (the electrical feeder equipment for trains) was made of an aluminum section under which was fixed a copper contact wire [3]. Nowadays the contact wire is composed of copper, steel-copper or aluminum-steel, W-Cu [1, 5-12, 13].

The aluminum alloys used to contact wire lines are AlMgSi0.5, A1Si3NiMg, AlCu2MgNiFeSi, etc. Among these alloys, in terms of resistivity, the lowest resistivity of the Al alloy had AlMgSi0.5 (34.34 ×10-3μΩ mm^2/m), than AlSi3NiMg (39.73 ×10-3μΩ mm2/m) and followed by AlCu2MgNiFeSi alloy (44.76 ×10-3 μΩ mm2/m) [4, 14]. However, AlCu2MgNiFe, has a low corrosion resistance. Compared to copper (17.73 ×10-3μΩ mm2/m) resistivity values of aluminium alloys are almost double, but they compensate by increasing section in aluminum wires [4].

An important role of aluminum resisitvity is played by the main contents of Fe and Si impurities, their level depending upon the operating conditions of the electrolysis tank. It is therefore an initial choice of Al conductors according to the percentage amount of alloying elements or impurities.

In Table 1 is presented the increasing resistivity at different additive elements / impurities [4, 12].

Table 1. Resistivity depending on impurities/elements.

Alloying element/ impurity	Solubility, wt.%	Increasing resistivity μΩcm/wt.%
Fe	0.052	0.058
Si	1.65	0.088
Cu	5.65	0.03
Mg	14.9	0.22
Zn	82.8	0.023
Li	4	0.68
Ni	0.05	0.061
Zr	0.28	0.044
Cr	0.77	0.18
Mn	1.82	0.34
Ti	1	0.12
V	0.5	0.28

The influence of Ti and V impurities can be reduced by treating the metal with B which leads to the formation of TiB2 or AlB2 compounds with reduced influence on the Al resistivity. This is achieved either by treatment of liquid metal with AlB pre-alloys or by treating the bath with fluxing agents containing boron (borax, boron-fluoride compounds etc.).

Mechanical and electrical characteristics of wire in different states, are presented in Table 2 [12, 15].

Table 2. Mechanical and electrical characteristics

State of Φ9.5 mm wires	Tensile strength , MPa	Resistivity, μΩcm
Soft	80-90	2.74-2.76
Hard	115-130	2.76-2.795
Annealed	65-75	2.7-2.715

It is found that high mechanical strength correspound to high material resistivity. It worth noting, that, the for large diameter and being in soft (annealed) state, the electrical resistance of the wire is low. AlMgSi alloy (ASS / L type) current use as wire electrical conductors it contains 0.53% Mg, 0. 53% Si and Fe is below 0.33%. The alloy is hardened by heat treatment due to a large compound of Mg_2Si that precipitate in the material. The solution treatment is made in an air circulated furnace at about 560°C for a period of about 10 hours, followed by water quenching and after that aging at l60° C for 5 hours [16, 17]. The resistivity of AlMgSi alloy in different technological stages are: i) 2.95-3.15 μ Ω cm, in cast and rolling condition at Φ 9.5 mm, ii) 3.4-3.5μΩcm in solution treated state, iii) 3.4-3.6μΩcm for Φ3.45 mm wire drawing state, iv) 3.15-3.25 for artificial quenching state. Note that in this case, regardless of mechanical resistance, the alloy has a relatively constant resistivity ranging within 3.15-3.6 Ω μ cm, except for the alloys which are in casting and molding state. In this case, the resistivities are slightly below these values [4, 12].

2. Hot extrusion of Al-Mg-Si aluminum alloys

2.1 Theoretical aspects of extrusion

Many researchers studied the factors and the parameters which are involved in hot plastic deformation of different materials [17-21]. The main factors that characterize the extrusion process are: the degree of extrusion (extrusion ratio) and extrusion speed.

The degree of extrusion depends on the following factors: a) chemical composition and properties of metallic materials subjected to extrusion; b) extrusion machine strength (degree of deformation increases directly with proportion to the maximum force that can develop hydraulic press; c) extrusion temperature (degree of deformation can be increased as the temperature is higher ingot; in this case, metal material possesses better plasticity); d) temperature of the container/"contenor"; e) speed of extrusion as defined by the length of the hole that leaves the die of extruded product, per unit of time. Between extrusion speed "v_e" and the punch speed "v_p" there is a direct correlation:

$$v_e = \lambda\, v_p \tag{1}$$

Therefore at a constant speed of the punch, the degree of deformation and extrusion speed increases proportionally. Extrusion speed also depends on the: i) chemical composition of extruded metallic material (as speed will still decrease, the percentage of alloying elements increases); ii) the geometry of the product obtained (speed will be even less with how extruded or profiles bars have a more complicated form and it thick walls or lower ribs; iii) mechanical properties of extruded products. It is known that as the degree of extrusion is increase, the strength and properties of extruded products (tensile strength, yield strength) also increase, but they have lower plasticity properties.

Therefore certain extrusion ratio must be chosen to obtain all the mechanical characteristics of the finished products. We have to take into account also that as the extrusion ratio increase, the metallic material flow through the die orifice is getting complicated; increases die wearing, and may remain extruded profiles with additional stress [18]. Depending on the profile or rode section that is obtained by extrusion, for the same diameter of the semi-product and at the same rate of advance of the punch advancement, various degrees of deformation and different strain rates will result. [17-19,22].

However at a high degree of deformation and large strain rates, there is an increase of deformation temperature due to the thermal deformation. If the initial temperature of the semi-product is near the upper permissible temperature, then at high degree of deformation and large strain rates, it can easily exceed this limit, and the final product will get poor quality.

Consequently, to achieve the desired qualities, we need to make sure to obtain the optimum deformation temperature in the deformation area [23]. To achieve optimum deformation temperature, we need to consider the correlation that exists between the initial temperature of the semi-product, the resulting strain and strain rate used. Thus, at high degrees of deformation, we can use lower deformation speeds and vice versa. To calculate the extrusion force we can use the following equation:

$$F = A \times p \times \ln\frac{A}{a} + \mu \times p \times D \times L \tag{2}$$

Where: μ is friction coefficient; A is area of the container die; D is the container die diameter; p is resistance of deformation; a is area of contact line (wire); L is the length of contact wire (line) [17, 21].

2.2 Design and manufacturing of extrusion die

In the case of hot extrusion of aluminum alloys AlMgSi0.5, the main technological parameters that are taken into account for round and square bars are: the ingot temperature 410-520°C, the container /"contenor" temperature which is 300-450° C, the admitted/ allowed extrusion degree of 5-300 % and the optimum extrusion degree of 0-120%, and also, the allowed strain rate which are situated between 10 and 90 m /min and the optimal one, of 20-60 m / min [22].

The geometry and the extrusion die are very important aspect of die design.

The design of dies for continuous extrusion of materials takes into account the following aspects:

a) to design at accurate dimensions and the product shape; b) to obtain a maximum working life; c) to have a maximum length of the extruded sections; d) to achieve a high extrusion speeds; e) to get low manufacturing costs [24].

According to others researchers [25] in design and construction of die we must consider the following parameters: the flow pattern, maximum specific pressure, the shape geometry of the section, wall thickness and tongue sizes, shape of the bearing surfaces and the tolerances of the sections.

The dimensions of the die holes will be established only after he adopted their number and their location on the die surface. The number of holes needed to be processed by extrusion die (n) depends on the section of the container or semi-product (Ss), the cross section of the extruded profile (Sc) and the degree of extrusion (X) to be made to ensure the required product properties finished.

Thus from the degree of extrusion relationship we can calculate the number of holes [18]. The choice of the number of holes of the die depends on production volume to be made for that product, the possibilities for design and execution of dies, as well as the minimum distance that can be allowed between two neighboring holes (in terms of resistance matrix material).

Regarding how to place the calibrated holes on the die surface,we must ensure less uneven flow rates of material through the die orifice/hole. Therefore if asymmetric profiles, unbalanced hole die axis will be placed against the axis so that the container has a small specific area (ratio of perimeter and area section) [18].

3. Experimental procedure

Experimental researches has been made at ALRO Slatina S.A. and consisted in continuous extrusion forming of a lot of contact wires for railway vehicles, from AlMgSi0.5 alloy. AlMgSi0.5 alloy was elaborated, semi-casted into rods (ϕ175 mm in section).

The rods were homogenized, cut at ϕ175 × 500 mm dimensions, quality controlled and degreased.

Contact wires were obtained by continuous extrusion, and then quenched on press, wrapped on the drum and artificial aging.

The elaboration of AlMgSi0.5 alloy (according with Romanian standardization STAS 7608/83), was done in a 9 tons capacity furnace, with automatic temperature control. The melt was degassed with chlorine and cleaned the metal bath surface.

The semi-continuous casting of alloy was made in rods of ϕ 175 × 6000 mm in dimensions, on casting plant, equipped with 4.5 tons capacity furnace, heated with methane gas (automatic temperature control) and degassing facility. After casting the rods were homogenized at 520° C / for 16 hours in a furnace methane gas atmosphere.

Then the rods were cut into ϕ175 × 500 mm samples. For experiments, we were used 250 mm in length samples, to analyze the quality of joining heads and to see the eventually defects that may occur in these areas.

The samples were ultrasonic controlled (on "Krauteramer" installation) and degreased.

The chemical analysis was performed with a spectral device Spectrolab 92 type, from Germany.

Were prepared 4 samples with size ϕ 175 x 250 mm (for preliminary tests) and then, 49 samples with size ϕ 175 x 500 mm (from charge A) and 20 samples with dimensions ϕ 145 x 580 mm (from charge B). By applying the equation (2) with p = 2.5 daN/mm2, μ=0.3 and a= 246 mm^2, we obtained the applied extrusion force F_1= 341.2 ton force (t f) for samples from charge A, and the extrusion force F_2= 236.7 ton force for samples from charge B.

Continuous extrusion was performed on a horizontal hydraulic press of 1650 tons force Farrell Bridge type and heating was done in induction furnaces on the extrusion press. For these tests an extrusion die with chamber was designed and executed as shown in the Fig. 1.

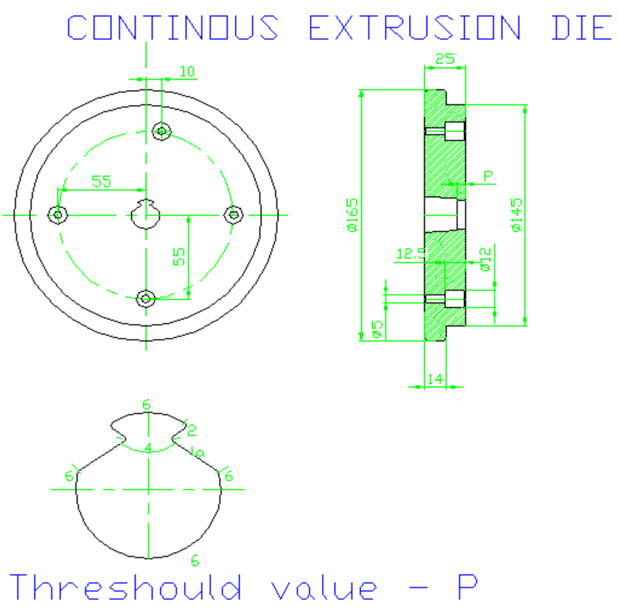
The other sub-assemblies were reused from ϕ 20 mm rods. The set of tools and devices used to pressing was composed of: bushing die(1), pre-chamber(2), extrusion die (3), support ring no.1 (4), support ring no.2 (5) and pressing mandrel (8), as you can see in Fig. 2 samples were successively charged into the furnace and heated to 520°C. The heat treatment (hardening by quenching in water) of the material occurred on the extrusion press; the plant being at approx. 2 m out from the extrusion die. After extrusion, we removed the rest remains from the plastic deformation by extrusion and it were placed the following degreased samples of materials in the sub-assembly "contenor" (6), for extrusion.

The remaining metal in the chamber of the extrusion die was mixed with the metal for the next extrusion, carrying out the welding of the ends of the extruded samples on a conical surface (cone welding). The pressing degree achieved by extrusion was 118 and it is situated at the upper limit of the optimum values for this alloy type [22]. The temperature of the sub-assembly (6) was approx. 400°C, and the piston speed was between l00-200 mm/min.

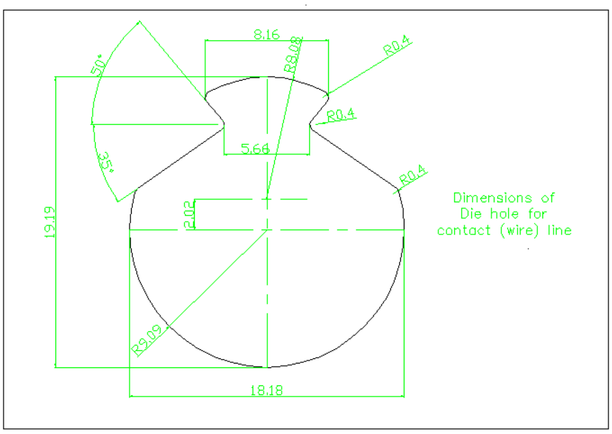
From cooling zone to the surface of the drum, the profile moves forward to a cooling bed with an approx. 40 m length and the wrapping of the profile was made on a wooden drum, M18 type. 49 pieces were extruded successively at size ϕ175 x 580 mm from charge A and 20 pieces at ϕ 145 x 580 mm were extruded from charge B, and we obtained 1380 kg continuous wire-contact from AlMgSi 0.5 alloy. To analyze the quality of joining were made macrostructure analysis on samples taken from the welding area. After extrusion and quenching on the press, the AlMgSi0.5 alloy wire were wrapped on a wooden drum and aging at 155°C for 14 hours, cooled in air.

Aging was done in a furnace room, with radiant burner tubes, heated with methane gas, and had self-regulation air recirculation and with automatic temperature control.

The samples were analyzed of micro-structural point of view and mechanical characteristics.



a



b

Fig. 1. The design of extrusion dies: a) Continous extrusion die; b) dimensions of the die hole.

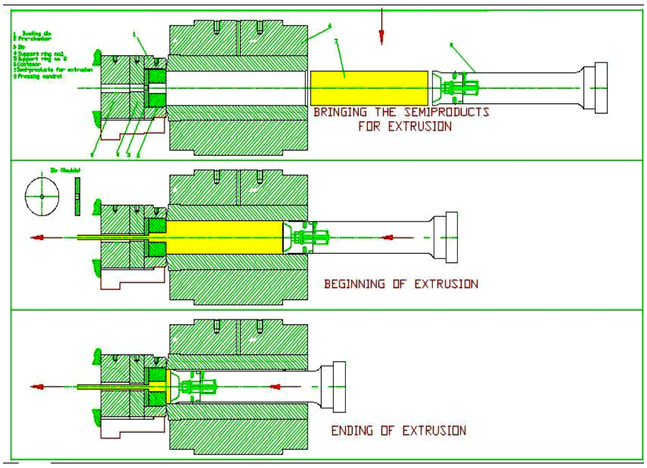


Fig. 2. The continuous extrusion steps and the components of extrusion pres: die(1), pre-chamber(2), extrusion die (3), support ring no.1 (4), support ring no.2 (5), sub-assembly "contenor" (6), semi-products material for extrusion (7) and pressing mandrel (8).

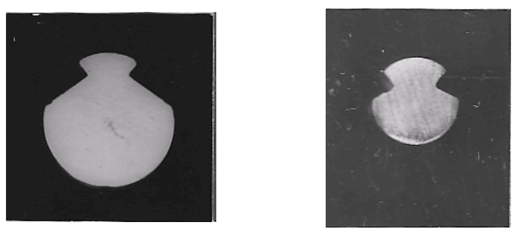
3. Experimental results and discussions

The chemical compositions of AlMgSi0.5 alloy for contact wires, determined after elaboration is presented in Table 3.

Table 3.

Chemical Composition, %	***Material Type***	
	Charge A	*Charge B*
Mg	0.575	0.463
Si	0.424	0.459
Fe	0.268	0.300
Cu	0.047	0.087
Cr	0.009	0.016
Mn	0.032	0.063
Ti	0.037	0.032
Zn	0.031	0.026
N	0.005	0.005
Al	balanced	balanced

We observe that the composition is according with STAS 7608/83 and DIN 1725/80 standardization. After elaboration, casting and continuous extrusion processing, we took samples of the contact wire, and we compared the macrostructure with a similar sample from copper (Fig. 3).



(a) (b)

Fig. 3 Macrostructural sample of (a) contact wire from AlMgSi0.5 compared with (b) macrostructural sample taken from copper wire.

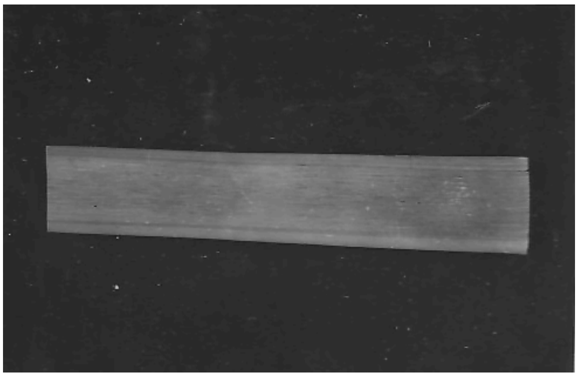
The obtained macrostructures from the area welding samples are presented in Fig. 4.

It appears that the material is compact, and the joining was being carried on a combination of conical surface with approx. 500 mm length. The force obtained in outside welding area was 3600-4000 kilogram-force (kgf).

The total tensile forces in cone welding area was about 3200 kgf, which represent 80-90% from the force obtained in outside welding area.

The analysis of fracture of welding area samples (Fig. 5) shows that rupture is ductile and it was not pulling on the inner surface of the cone, which shows that welding of the ends of samples is strong enough. We observed a ductile fracture in the two welded layers.

The microstructure of a sample took from the contact wire area after heat treatment is shown in Fig. 6. We observed precipitated compounds in solid solution.



(a)

(b)

Fig. 4. Macrostructures of the samples taken from the cone weld joining, at the ends of the contacct wire.

The obtained mechanical characteristics of the wire are:

Rm = 163-248 MPa, A = 15 - 18.5%, 46-87 HB. The total force for breaking the wire: F =4250-6450 kgf.

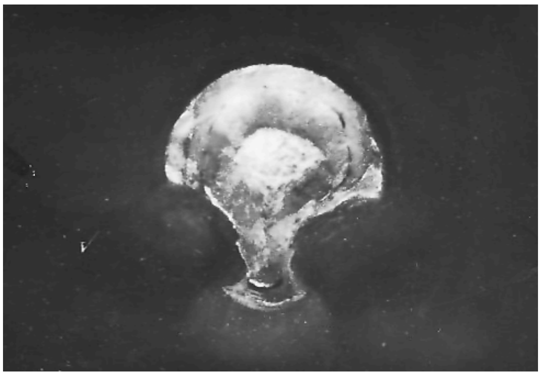


Fig. 5. The facture appearance of AlMgSi0.5 alloy specimes, taken from the welding cone.

4. Conclusions

In order to obtain aluminum contact wires/cables for trams or light rail was designed and executed an extrusion die. We succeed to obtain the contact line wires from aluminum alloy by the following processing route: elaboration, semi-continuous casting, homogenization and continuous extrusion of AlMgSi0.5 aluminum alloy, followed by heat treatment (quenching in water on the extrusion press and artificial aging).

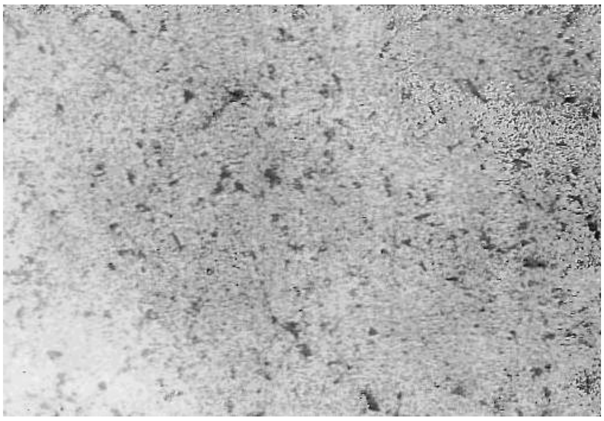


Fig. 6. The microstructure of a sample taken from the contact wire area after heat treatment, at etched conditions, 0.5%HF, x250 Magnification.

We obtained the following characteristics: Tensile strength Rm = 163-248 MPa, Elongation A = 15 -18.5%, Brinell Hardness 46-87 HB and the total force for breaking wire: F =4250-6450 kilogram-force.

It was noted that although the minimum tensile strength obtained is less than 200 MPa (Rm = 163-248 MPa), the value of total tensile forces F = 4250-6450 kgf in aluminium contact wire is superior to the copper wire total tensile forces (3500Kgf according with PN-64/E-90090 standardization and Romanian standard STAS 686-71).

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