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NEW ALUMINIUM ALLOYS FOR ELECTRICAL WIRES OF FINE DIAMETER FOR AUTOMOTIVE INDUSTRY

NOWE STOPY ALUMINIUM NA PRZEWODY ELEKTRYCZNE O MAŁYCH ŚREDNICACH DLA PRZEMYSŁY SAMOCHODOWEGO

In the recent years economic reasons have forced us to search for new applications of aluminium and its alloys in electrical engineering as an alternative material for the traditionally used copper. Presently aluminium wires with the diameter not exceeding 1 mm are used for the production of automotive conductors, accumulator cables and winding wires. In this case the possibilities for mass processing of aluminium into fine wires are significantly limited by the technological problems. The main reasons for the limited aluminium deformation properties, so important in the wire drawing process, are the high coefficient of friction, adherence of the material to the tool surface and too low plasticity resulting from the natural occurrence of silicone in the bauxite. Silicone causes cracking of the material as a result of which a net of micro-cracks forms on its surface limiting the wire deformation properties. Elimination or significant reduction of this negative phenomenon may be obtained by introducing iron to aluminium which by forming hard and high-melting chemical compounds such as Al_3Fe will help in self-cleaning of the wire drawing die surface by removing the adhered patches of aluminium and will lower the aluminium ductility threshold. Additionally, by binding silicone, iron improves the electrical conductivity of the material and also its plasticity liquidating the stress concentration points, particularly dangerous in case of the hardened fine wires.

The article presents the analysis of the influence of iron addition on the properties and deformability of aluminium rod and aluminium wires as well as the results of the author's own research on unalloyed aluminium rod with varied iron content used for the processing of fine wires designated for the production of automotive bundles. It has also been proved that the increase of the content of iron does not significantly decrease the electrical conductivity of the material and enables drawing of the fine 0.1 mm wires on the industrial scale.

Keywords: fine Al wires, aluminium rod, iron in aluminium, CCR

Powody ekonomiczne prowadzą w ostatnich latach do poszukiwania coraz to nowszych zastosowań aluminium i jego stopów na cele elektryczne jako zamiennika tradycyjnie wykorzystywanej miedzi. Nowy trend polega na konstrukcji wiązek przewodów samochodowych, kabli akumulatorowych, a także przewodów nawojowych z drutów aluminiowych o średnicach poniżej 1 mm. Naturalnym ograniczeniem w tym względzie są trudności technologiczne w przetwórstwie aluminium na druty o małych średnicach. Głównym powodem ograniczonej odkształcalności aluminium w procesie ciągnienia jest wysoki współczynnik tarcia, nalepianie się materiału na ścianie narzędzia oraz niska plastyczność spowodowana naturalną obecnością krzemu w boksycie, który – prowadząc do siatki powierzchniowych mikropęknięć – ogranicza odkształcalność drutu w schemacie ciągnienia. Wyeliminowanie lub znaczne ograniczenie tego negatywnego zjawiska można uzyskać poprzez wprowadzenie do aluminium żelaza, które tworząc twarde i wysokotopliwe związki typu Al_3Fe samooczyszcza powierzchnię ciągadła z nalepień aluminiowych i przesuwa próg ciągliwości aluminium. Ponadto żelazo wiążąc krzem polepsza przewodność elektryczną materiału oraz jego plastyczność likwidując miejsca koncentracji naprężeń, szczególnie niebezpieczne w umocnionych drutach o małych średnicach.

W artykule przedstawiono analizę literaturową wpływu dodatku żelaza na własności i odkształcalność walcówki i drutów aluminiowych oraz wyniki badań własnych nad procesem ciągnienia walcówki aluminiowej o różnej zawartości żelaza na druty o małych średnicach przeznaczone na wiązki samochodowe. Wykazano, że wzrost zawartości żelaza nie pogarsza istotnie przewodności elektrycznej materiału i pozwala na ciągnienie drutów w skali przemysłowej o średnicach 0,1 mm.

1. Introduction

Abundant occurrence of crude-bauxite in the lithosphere and wide availability of aluminium alloys' very attractive properties have made this metal broadly applicable in the contemporary world. It is used, in particular, in the transportation, construction, and power sectors, as

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well as in the packaging industry. Uniform demand for aluminium in various branches of the economy makes its consumption consistently growing [1]. The metal's natural properties including, but not limited to, its low density, resistance to atmospheric corrosion, and high electrical conductivity, which relative to its mass exceeds that of copper, have ruled its quite common applications (tab. 1.)

TABLE

Comparison of Cu and Al typical features

Feature	**Cu**	**Al**	**Cu/Al**
Density, **g/cm3**	8,9	2,7	3,3
Electrical conductivity, **MS/m**	58	36,7	1,6
Price, **$/t***	3 430,00	1 751,00	1,96
*24.11.2008 price of London Metal Exchange			

One of the largest application areas of aluminium and its alloys is the transportation sector. Use of aluminium significantly increases payloads of road, rail, and water transportation means, reduces fuel consumption and hence environmental pollution, as well as improves travel comfort and safety.

In 2005 the aluminium share in car weight amounted to 132 kg and its further growth is expected up to ca. 160 kg by 2010. On average, 100 kg mass reduction achieved on a passenger car saves 0.35 litre of fuel per 100 km and 9 grams of CO_2 per km at the car exhaust pipe. Moreover, such vehicle weight reduction is accomplished without compromising the travel safety [2].

Therefore application of aluminium components in the automotive industry significantly reduces environmental pollution and leads to reduced emission of greenhouse gases through car exhaustion pipes. Also ease of aluminium recycling, which translates into saving of ca. 95% of the energy necessary for primary aluminium production, contributes to environmental protection. An increase in the car weight has been observed over the recent years in Europe, despite the fact that the weight directly translates into fuel consumption. It results from changes in consumer preferences and manufacturers' introduction of more comfortable and safe cars to the market. To improve these parameters vehicles are provided with larger subassemblies, which – consequently – increases their weights.

Another advantage of introducing aluminium subassemblies to car designs is increased power to weight ratio, which boosts the vehicle acceleration and shortens braking distance. Moreover, vehicle weight reduction at retained breaking performance results with smaller brakes, i.e. an additional weight reduction. A lighter car is easier to control at road emergencies, which improves safety of the driver, other travellers, and pedestrians on the road.

2. Aluminium with iron micro-additions

Consistent vehicle mass reduction has made car design engineers search for new aluminium alloys so far unknown to the market. Copper, so far used for car wiring bundles and battery cables, is now squeezed out by aluminium. Use of pure aluminium is practically impossible because of the metal's low limiting deformability and its adhesion to die walls. In practice no aluminium wires thinner than 1 mm are manufactured. Hence the idea to introduce alloy micro-additions that will extend the ductility threshold towards smaller diameters. Iron is a good element suitable for this purpose. Adding a small amount of iron to aluminium results in the alloy's slight electrical conductivity reduction (by ca. 10% at 1% weight Fe content), whereas the content's increase over 0.6% of Al weight does not decrease the product's electrical conductivity any further (compare Fig. 1). Another advantage of adding Fe to Al is that it produces high-melting Al_3Fe compounds that at drawing clean die walls of adhered Al patches thus extending the material's deformability towards smaller diameters.

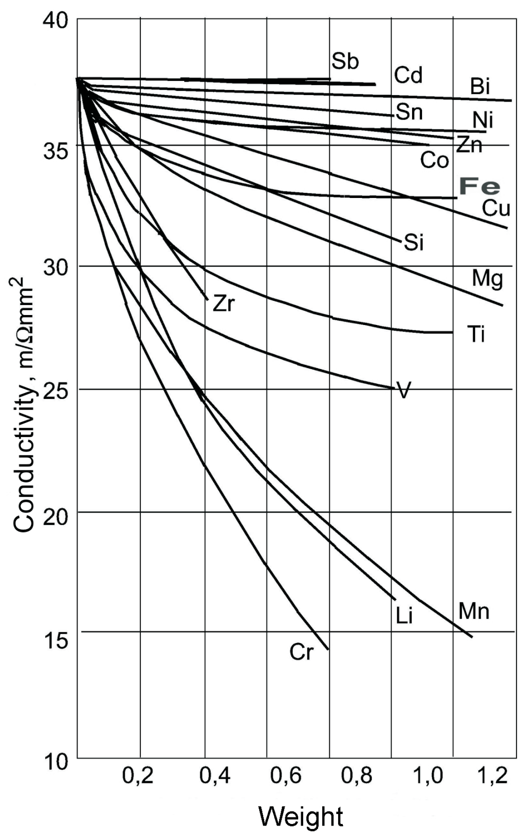

Fig. 1. Detrimental effect of various elements on the conductivity of 99.99% Aluminium [3]

The Al_3Fe phase existing in equilibrium with aluminium solid solution is formed from the melt at a temperature of 1152°C and a concentration of 40,8% Fe. However, the critical reviews (Massalski 1986, Lyakishev, 1996) point to the peritectic formation of the Al_3Fe phase: $L+Al_5Fe_2 \rightarrow Al_3Fe$. The properties of the Al_3Fe phase are as follows: the density γ = 3.896 g/cm^3 (Mondolfo, 1976) or 3.78 g/cm^3 (Hatch, 1984); linear expansion coefficient $\alpha = 15.2 \text{x} 10^{-6}$ K^{-1} (in the range from 27 to 627°C); electrical resistivity ρ = 0.5 Ohm m; Vickers hardness HV = 8 GPa (at 27°C), 5.7 GPa (at 357°C) and 3 GPa (at 627°C) (Mondolfo, 1976): Young's modulus E = 136 GPa (Eskin and Toropova, 1994). The microhardness of the Al_3Fe phase at 20°C is 11.47 GPa [4]. The maximum Fe in Al solubility in liquid state at ca. 650°C amounts to ca. 0.052% of Fe weight, and at 500°C it decreases to 0.02% of Fe weight (Fig. 2). Small iron amount entering the solution extract silicon, which is a natural bauxite component, producing iron-silicone compounds and hence increasing the product's electrical conductivity.

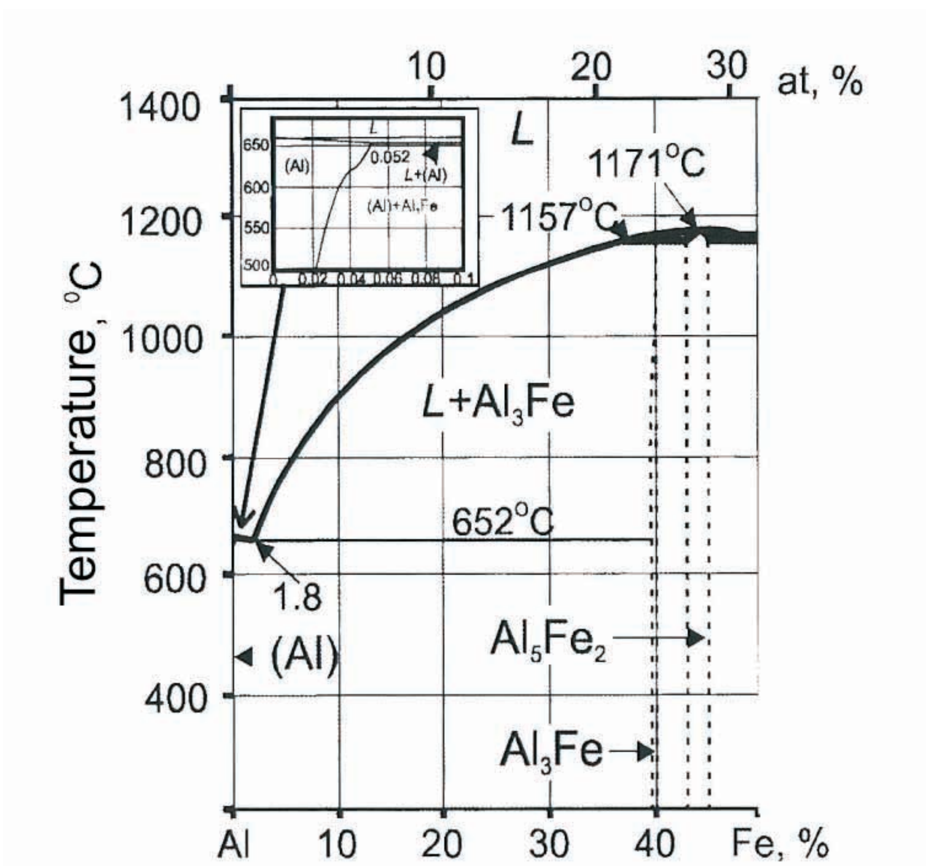

Fig. 2. Phase diagram of Al-Fe from aluminium side [4]

3. Literature analysis

Results of a Japanese team's research of the effect of iron to aluminium 0.3 – 0.9% weight addition on mechanical and electrical properties of low-diameter wires [5] are presented below. Aluminium of high chemical pureness of 99.9% with Al-Fe prealloy (50% of Fe weight) was melted in strictly predefined proportions at an inductive furnace in argon shield, continuously cast, then rolled into wire rod of 8 mm diameter, and finally drawn to wires of 0.3 mm diameter. Increasing Fe addition content in aluminium caused quicker strengthening of the material compared to pure Al and higher yield point at the cost of a slight deterioration of its electrical conductivity (Fig. 3).

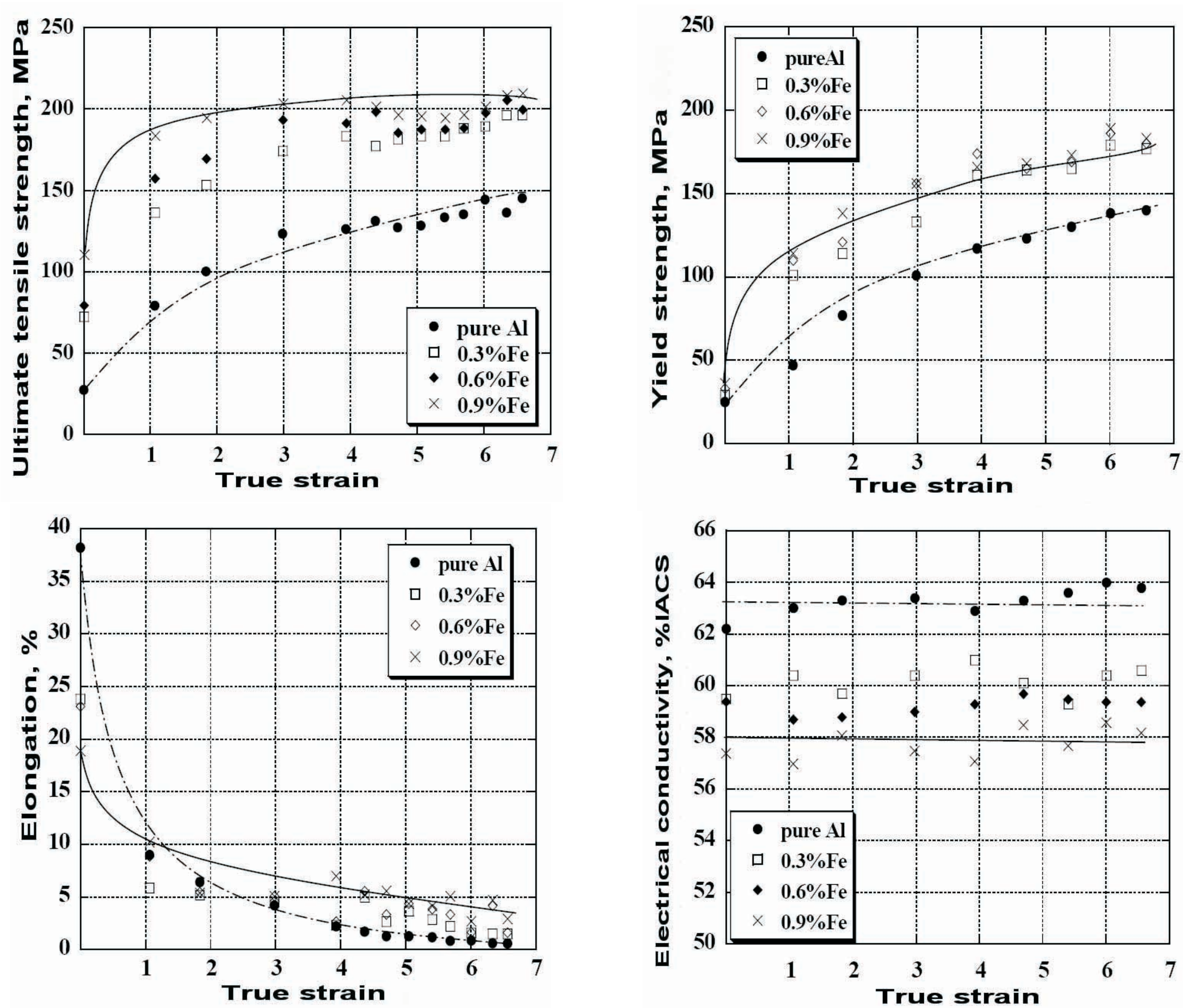

Fig. 3. Mechanical properties and electrical conductivity drawing wires of aluminium rod with Fe element [5]

4. Own research

The input materials were aluminium rod (8176) of 9.5 mm diameter produced in the CCR line by the Continuus-Properzi method consists of 0.1% Fe weight content in H11 state, which was drawn to 2.0 mm wire on a laboratory chain drawbench; and rod with 0.5% Fe weight content drawn under laboratory condition to 0.5 mm wire. The wire's mechanical and electrical properties were examined after each drawing operation. Another input material was 9.5 mm AlMgSi alloy rod of 6101 grade produced by the same CP method consists of 0.21% and 0.36% Fe weight contents, then annealed in a laboratory furnace at 190°C for 5 hours, and finally drawn to 3 mm wire. In both cases the research objective was to determine the iron addition effect of on the wire's mechanical and electrical properties. In addition scanning analysis was completed of the AlMgSi rod's fracture after a single-axial tension test. All wires so manufactured met requirements of the relevant standard [6].

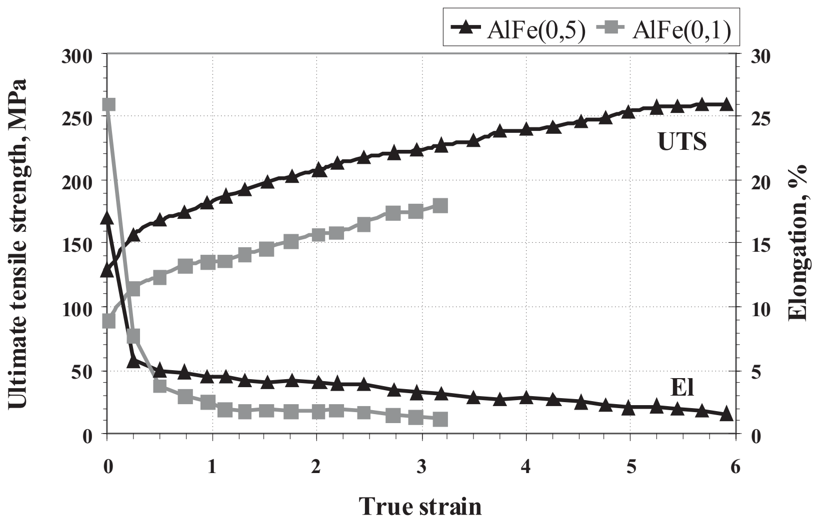

Fig. 4. Influence iron addition on work-hardening in laboratory drawing process

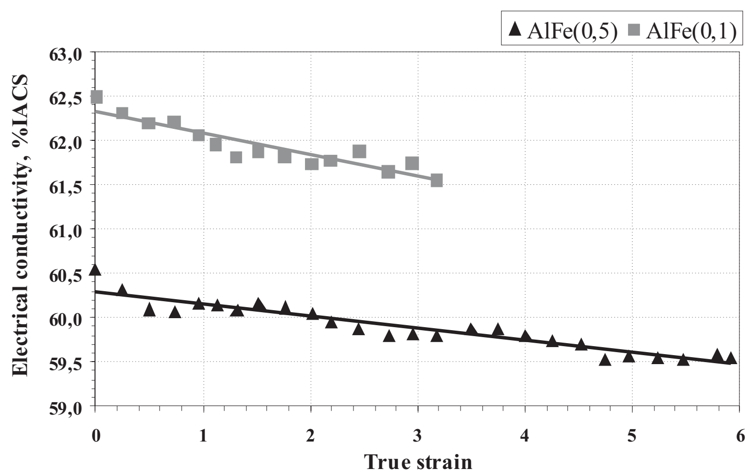

Fig. 5. Influence iron addition on electrical conductivity in laboratory drawing process

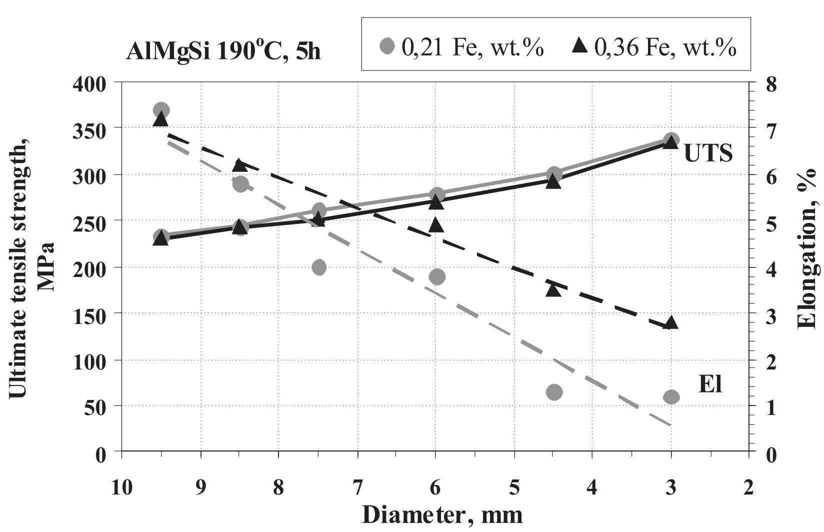

Fig. 6. Mechanical properties of AlMgSi wires

An addition of 0.5% Fe weight resulted with a significant tensile strength increase compared to wires drawn of the typical Aluminium rod (Fig. 4) at the cost of slight electrical conductivity deterioration (Fig. 5). An interesting phenomenon was observed as regards wires drawn of the alloy rod. No differences in mechanical properties and fracture structure were observed in 6101 grade rods of different Fe contents (Fig. 7), which were subject to preliminary thermal processing. However the plasticity of 3.00 mm wires with 0.36% Fe weight content exceeded that of wires with 0.21% Fe weight addition (Fig. 6).

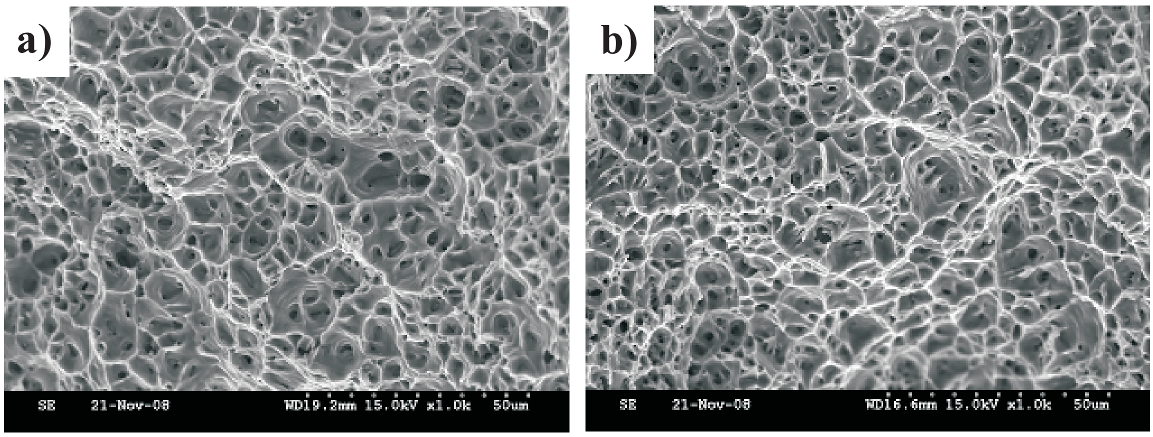

Fig. 7. AlMgSi rod fracture with Fe addition: a) 0,21mass%, b) 0,36mass% in 1000x magnification

5. Summary and final conclusions

Based upon the completed research the following conclusion may be drawn:

- Addition to Al (8176) of 0.5% Fe weight improves drawing conditions, which allows extending the material's ductility threshold to 0.15 mm diameters with no significant deterioration of its electrical properties.
- In 8176 grade aluminium wires with increased Fe content feature higher plasticity in tensile tests, which may be associated with better friction conditions on the tie surface and non-occurrence of the surface micro-crack net that is otherwise typical for this material.
- The foregoing remarks concern AlMgSi wire alloys as well.
- Car wiring bundles may be manufactured of aluminium and AlMgSi alloys with iron additions with properties competitive to those of copper wires.

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