International Journal of Earth, Energy and Environmental Sciences
ISSN: 2517-942X
Vol:9, No:5, 2015

A Metallography Study of Secondary A226 Aluminium Alloy Used in Automotive Industries

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Abstract**—**The secondary alloy A226 is used for many automotive casting produced by mould casting and high pressure die casting. This alloy has excellent castability, good mechanical properties and cost-effectiveness. Production of primary aluminium alloys belong to heavy source fouling of life environs. The European Union calls for the emission reduction and reduction in energy consumption therefore increase production of recycled (secondary) aluminium cast alloys. The contribution is deal with influence of recycling on the quality of the casting made from A226 in automotive industry. The properties of the casting made from secondary aluminium alloys were compared with the required properties of primary aluminium alloys. The effect of recycling on microstructure was observed using combination different analytical techniques (light microscopy upon black-white etching, scanning electron microscopy - SEM upon deep etching and energy dispersive X-ray analysis - EDX). These techniques were used for the identification of the various structure parameters, which was used to compare secondary alloy microstructure with primary alloy microstructure.

Keywords**—**A226 secondary aluminium alloy, deep etching, mechanical properties, recycling foundry aluminium alloy.

I. INTRODUCTION

APPLICATION of aluminium alloys provides up to 55 % weight savings in comparison with steel. The A226 is casting alloy in which silicon is the principal alloying element. The A226 sand, die, and permanent mould castings are critically important in engine construction; engine blocks, cylinder heads, carburettors, and transmission housing are proven components.

The car production has been increasing and is important to reduce the energy cost, greenhouse effect, problems to the environment etc. associated with the production of casting from primary aluminium alloy. Care of environment in industry of aluminium is connected with the decreasing resource consumptions as energy, materials, waters and soil, with increase recycling and extension of products life [1]-[3].

The production of one metric ton of aluminium from bauxite requires about 17 000 kWh of electricity, while the same amount of recycled aluminium consumes approximately 750 KWh [4]. The remelting of recycled metal saves over 95 % of the energy needed to produce primary aluminium alloy [1]-[3].

Due to the increasing production of recycled aluminium cast alloys their strict microstructure control is necessary, because the predominant objective in the design of aluminium alloys is to increase strength, hardness, and wear resistance, creep, stress relaxation, or fatigue. Effects on these properties are specific to the different combinations of alloying elements, their alloy phase diagrams and to the microstructure of solidification, thermomechanical history, and heat treatment, or cold working [5].

The alloying elements came into solid solution in the matrix and form intermetallic particles during solidification. Influence of intermetallic phases to mechanical and fatigue properties depends on size, volume and morphology of these phases [6]. The formation of these phases should correspond to successive reactions during solidification with an increasing number of phases involved at decreasing temperature. Reactions were identified by [7] in (3XX.X) alloys and were listed the solid-state phases which can be described in the following way as the solidification path for the investigated alloy:

- Nucleation of α-Al dendrite network (liquids temperature aprox. 602°C). The exact temperature value mainly depends on the Si and Cu concentration in the alloy.
- Liq. → Al + $Al_{15}(Fe, Mn)_3Si_2$ aprox. 590 ºC, [7] reports also the occurrence of the $Al_{15}Mn_3Si_2$ phase, which was not detected during the investigation).
- Liq. → Al + Si + Al_5FeSi phase within the range of 575-507 ºC, leading to a further localized increase in Cu content of the remaining liquid.
- Liq. → Al + Al_2Cu + Al_5FeSi + Si, reduction of temperature allows nucleation of Cu-enriched eutectic (Al+Al_2Cu) between 525 and 507 ºC.
- Liq. → Al + Si + Al_2Cu + $Al_5Mg_8Cu_2Si_6$ at 507 ºC
- End of the alloy solidification (solidus temperature) aprox. 483 ºC.

Therefore, the aim of this study was to quantify the properties and microstructure of secondary aluminium alloy versus primary aluminium alloy. The analysis of the A226 cast alloy in this work is the part of a larger research project which was conducted to investigate and to provide better understanding of the structure parameters influence on mechanical properties in recycled (secondary) aluminium cast alloy.

II. EXPERIMENTAL MATERIAL

The secondary A226 (AlSi9Cu3) cast alloy was used as an experimental material. The A226 cast alloy has lower

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corrosion resistance and is suitable for high temperature applications (dynamic exposed casts, where are requirements on mechanical properties not so high) - it means to max. 250°C. The chemical composition of primary A226 alloy obtained from standard (EN 1706) and secondary aluminium alloy (experimental material) according to results with using an arc spark spectroscopy shows Table I.

The secondary alloy (prepared by recycling of aluminium scrap) was received in the form of 12.5 kg ingots. Experimental material was molten into the permanent mould (chill casting), which were preheated for 250 °C. The melting temperature was maintained at 760°C ± 5°C. Molten metal was purified with salt AlCu4B6 before casting and was not modified or grain refined. The A226 castings were not heat treated, too.

TABLE I
CHEMICAL COMPOSITION WT %

Elements	Si	Cu	Mn	Zn	Mg	Ni	Pb
Primary A226 (EN 1706)	8.0 - 11.0	2.0 - 4.0	0.55	1.20	0.15 - 0.55	0.55	0.35
Secondary A226	9.4	2.4	0.24	1.0	0.28	0.05	0.09
Elements	Fe	Ti	Sn	Cr	other	Al	
Primary A226 (EN 1706)	0.6 - 1.1	0.20	0.15	0.15	0.25	rest	
Secondary A226	0.9	0.04	0.03	0.04	-	rest	

III. EXPERIMENTAL PROCEDURE

A. Mechanical Properties

The experimental tensile and hardness specimens for experimental procedure were made from the casting with turning and milling operation. Mechanical properties were measured according to the standards: STN EN 10002-1 and STN EN ISO 6506-1.

Hardness measurement for secondary aluminium alloy was performed by a Brinell hardness tester with a load of 62.5 Kp, 2.5 mm diameter ball and a dwell time of 15s. The evaluated Brinell hardness reflect average values of at least six separately measurements.

TABLE II
MECHANICAL PROPERTIES

Primary A226 alloy, according to EN 1706			
Mechanical properties	Tensile strength R_m	Elongation at break A_5	Brinell hardness
results	240 ÷ 310 MPa	0.5 ÷ 3 %	80 ÷ 120 HBS
Secondary A226 alloy-experimental material			
Mechanical properties	Tensile strength R_m	Elongation at break A_5	Brinell hardness
results	211 MPa	1 %	98 HBS

Tensile strength was measured on testing machine ZDM 30. The evaluated R_m and A_5 reflect average values of at least six separately bars. The results of mechanical properties are documented in Tab. II.

The results of mechanical properties of secondary A226 cast alloy shows that this material has lower value of mechanical properties in comparison with primary aluminium alloy. The lower mechanical properties led to analyse the influence of various structure parameters, because experimental material was not modified, grain refined or heat treated.

B. Microstructure of Experimental Material

Microstructure of hypoeutectic A226 cast alloy is given by the binary diagram, therefore is expected formation α-phase, eutectic (α-phase + eutectic Si) and various types of intermetallic phases. Microstructural features are products of metal chemistry and solidification conditions; therefore the real microstructure of secondary aluminium alloys can be different.

Metallographic samples for the study were cut from the selected tensile specimens (after testing) and hot mounted for metallographic preparation.

The microstructures were studied using an optical microscope Neophot 32 and scanning electron microscope (SEM) VEGA LMU II. The samples were prepared by standard metallographic procedures (wet ground on SiC papers, DP polished with 3 μmdiamond pastes followed by Struers Op-S and etched by standard etcher Dix-Keller, HNO_3,H_2SO_4), for study at the optical microscope.

The samples were etched by 0.5 % HF for SEM observation of structural parameters, EDX analysis using scanning electron microscope VEGA LMU II linked to the energy dispersive X-ray spectroscopy (EDX analyzer Brucker Quantax). Some samples were also deep-etched for 15 s in HCl solution in order to reveal the three-dimensional morphology of the Si-phase and intermetallic phases [8], [9].

The microstructure of secondary A226 cast alloy (experimental material) consists of: dendrites α-phase (Fig. 1), eutectic Si (Fig. 2), intermetallic Cu- rich (Fig. 3) and Fe-rich (Figs. 4-6) phases [10]-[12].

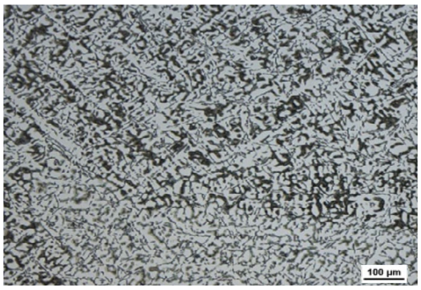
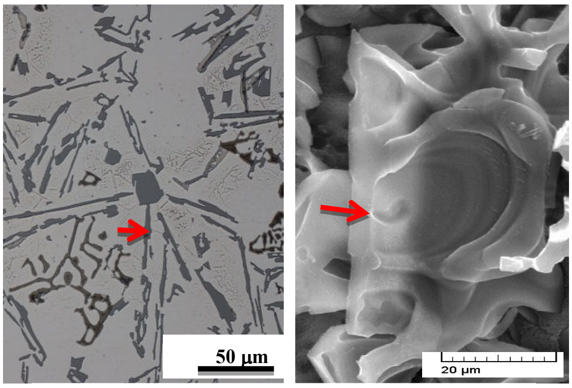


Fig. 1 The α-phase in secondary AlSi9Cu3 cast alloy, as-cast state. Optical microscope, etch. H_2SO_4

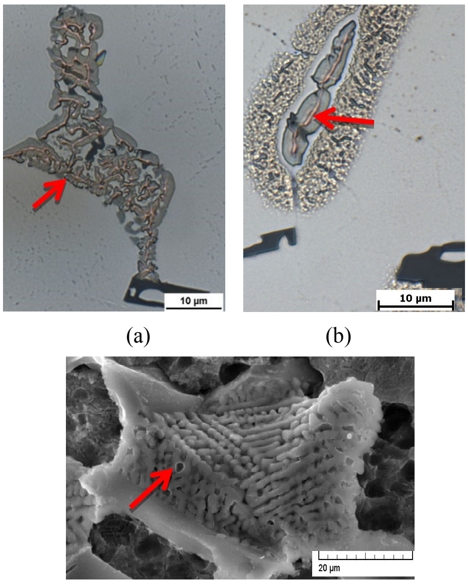
Experimental material was not modified or heat treated and so eutectic Si particles are in form of large platelets (Fig. 2 (b)), which on scratch pattern are in form of needles (Fig. 2 (a)). Si particles represent a large volume of the aluminium alloy's microstructure and therefore are very important to affect their morphology. Small, spherical and evenly distributed particles provide the optimum tensile, impact and fatigue properties of aluminium material [13], [14]. It can be suppose, that this morphology of eutectic Si causes a reduction in properties of secondary A226 cast alloy.



(a) (b)

Fig. 2 The eutectic Si in secondary AlSi9Cu3 cast alloy, as-cast state; (a) needles of eutectic Si; (b) platelets of eutectic Si – SEM

The experimental material belongs to Al-Si-Cu materials. The major precipitation addition is Cu in these materials. The amount of Cu up to 5 wt. % provides high strength properties and good toughness A226 castings. The common Cu-rich phases of primary A226 alloys are: Al_2Cu, Al-Al_2Cu-Si or $Al_5Mg_8Cu_2Si_6$ [6], [15], [16]. The Cu-rich phases: Al_2Cu (Fig. 3 (b)), Al-Al_2Cu-Si (Figs. 3 (a), (c)) were observed in secondary A226 cast alloy. The Al_2Cu phase was observed in compact formations (Fig. 3 (b)), but in a very small volume of experimental material. These phases were not easy observable by using deep etching - SEM.



(a) (b)

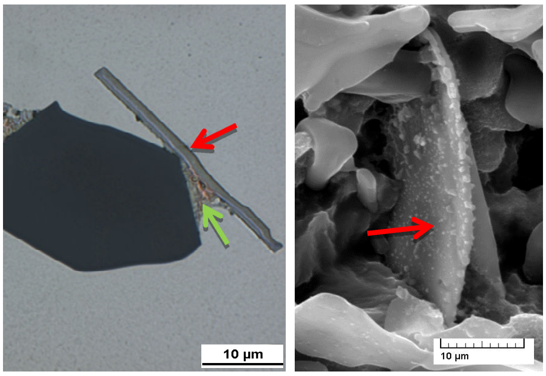
(c)

Fig. 3 The Cu-rich intermetallic phases in secondary AlSi9Cu3 cast alloy, as-cast state; (a) Al-Al_2Cu-Si; (b) Al_2Cu; (c) SEM-Al-Al_2Cu-Si

The second Cu-rich phase was observed in form of small particles interconnected with each other (Figs. 3 (a), (c)). It would be appropriate to use the precipitation properties of Cu addition for affecting morphology of Cu-rich intermetallic phases.

Iron is the most common and usually detrimental impurity in cast Al-Si alloys. Iron impurities can either come from the use of steel tools or scrap materials or be acquired during subsequent melting, remelting and casting, e.g. by contamination from the melting pot etc. Therefore, was a big assumption that in secondary A226 cast alloy will be a large number of Fe-rich phases.

The ASM Hanbook [16] points to the fact that in A226 cast alloy can be form phases $\alpha - Al_{15}(FeMn)_3Si_2$ and$\beta - Al_5FeSi$ on base Fe. The two main types of Fe-rich intermetallic phases were observed in secondary experimental material A226. The Al_5FeSi with monoclinic crystal structure (known as beta- or β-phase - Fig. 4) and $Al_{15}(Mn,Fe)_3Si_2$ (known as alpha- or α-phase - Fig. 5) with cubic crystal structure. The first Fe-rich phase (Al_5FeSi) precipitated in the interdendritic and intergranular regions as platelets (appearing as needles in the metallographic microscope - Fig. 4).



(a) (b)

Fig. 4 The Fu-rich intermetallic phases Al_5FeSi in secondary AlSi9Cu3 cast alloy, as-cast state; (a) Al_5FeSi needles; (b) Al_5FeSi platelets- SEM

It was also shown that the Al_5FeSi needles can act as nucleation sites for Cu-rich Al_2Cu phases (Fig. 4 – green arrow). These phases were in microstructure in a small volume, because "rule of thumb" the ratio between iron and manganese concentration of 2:1 was been met (experimental material: 0.9% Fe: 0.24% Mn). Also, the length of brittle Al_5FeSi platelets was not higher as 500 µm, which is the critical length, because so long phases can adversely affect mechanical properties, especially ductility, and also lead to the formation of excessive shrinkage porosity defects in castings [17]. It can be suppose, that their occurrence caused decreasing of secondary A226 properties (in comparison with properties of primary A226 alloy).

The deleterious effect of Al_5FeSi can be reduced by increasing the cooling rate, superheating the molten metal, or by the addition of a suitable "neutralizer" like Mn, Co, Cr, Ni, V, Mo, and Be. The experimental material had most common addition manganese and therefore was observed Fe-rich phases $Al_{15}(FeMn)_3Si_2$ in form „skeleton like“ or in form

„Chinese script“ (Fig. 5) in microstructure [18], [19]. These phases were observed in large volume of microstructure and were long.

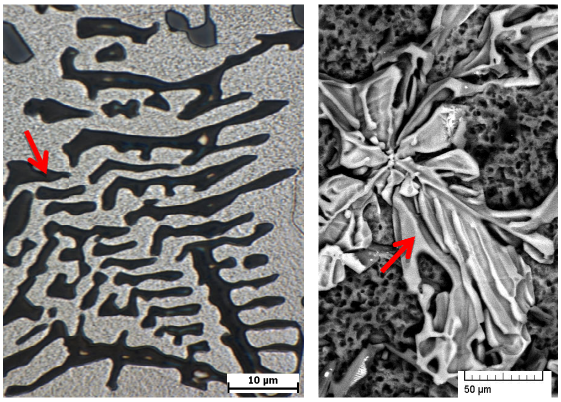


Fig. 5 The Fe-rich intermetallic phases $Al_{15}(FeMn)_3Si_2$ in secondary AlSi9Cu3 cast alloy, as-cast state; (a) $Al_{15}(FeMn)_3Si_2$ skeleton like;)b) $Al_{15}(FeMn)_3Si_2$ skeleton like - SEM

The compact morphology "Chinese script" (or skeleton - like) does not initiate cracks in the cast material to the same extent as Al_5FeSi does and phase $Al_{15}(FeMn)_3Si_2$ is considered less harmful to the mechanical properties than β phase [20], [21]. The experimental material is secondary-recycled and therefore in microstructure were observed the others Fe -rich and hard complex intermetallic multi-component sludge, $Al_{15}(FeMnCr)_3Si_2$- phases, too (Fig. 6).

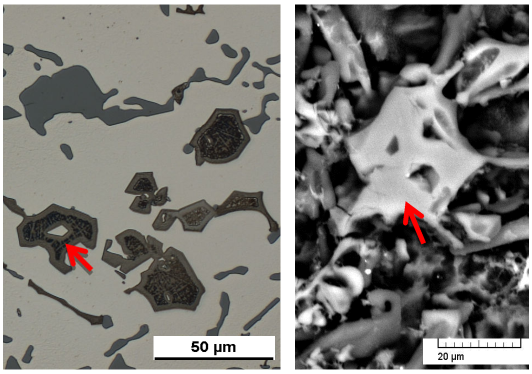


Fig. 6 The Fe-rich intermetallic phases $Al_{15}(FeMnCr)_3Si_2$ in secondary AlSi9Cu3 cast alloy, as-cast state; (a) $Al_{15}(FeMnCr)_3Si_2$ multi-component sludge; (b) $Al_{15}(FeMnCr)_3Si_2$ multi-component sludge-SEM

These intermetallic compounds are hard and can adversely affect the overall properties of the casting. The formation of sludge phases is a temperature dependent process in a combination with the concentrations of iron, manganese and chromium independent of the silicon content, therefore, it would be appropriate to use one of the possibilities for avoidance to formation these phases, because it could optimized properties of secondary A226 castings. According to literature ASM Handbook [16], if Mg is also present the pi- or π-phases can form - $Al_5Si_6Mg_8Fe_2$. This phase was not identified in secondary A 226 cast alloy with using experimental method.

To confirm of individual types of intermetallic phases were usedthe X-ray (mapping, line and point) analysis besides morphology studies by using optical microscope and SEM - deep etching. Due to the strictly localized interference of the electron beam and specimen material, the identification of the chosen particular phase precipitates may be carried out. This facility is of great importance in the case of Al-Si alloys, when the intermetallic phases have similar morphology and colour during observation under the metallographic light microscope (for example Fe-and Mg-rich phases). In this situation, X-ray microanalysis is an easy and repeatable method to unequivocally verify the phase composition of the alloy.

The method of X-ray analysis was simple method for phase identification, because we obtained the chemical composition data of each parameter.

The point, line and mapping EDX analysis of structural parameters of secondary A226 cast alloy show Fig. 7, 8, 9. The point X-ray microanalysis of ternary eutectic Al-Al_2Cu-Si performed in the marked point. The elements concentration (Cu, Si and Al) in this point shows Fig. 7.

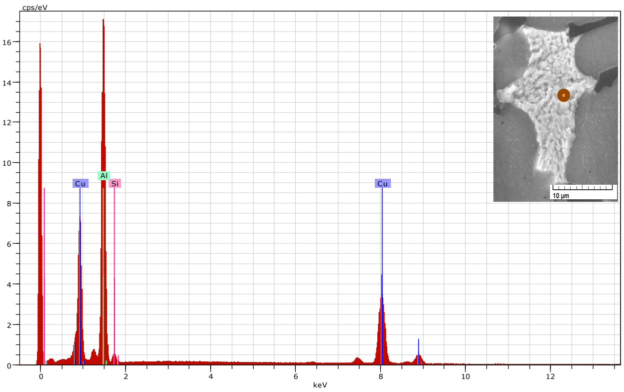


Fig. 7 The Al-Al_2Cu-Si phase identification using EDX point analysis, etch. 0.5 % HF

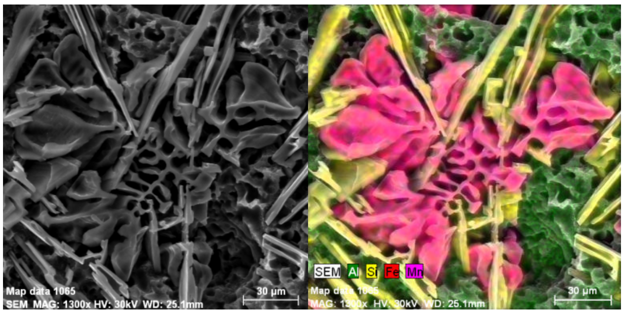


Fig. 8 The $Al_{15}(FeMn)_3Si_2$ phase identification using EDX mapping analysis, etch. HCl

The mapping microanalysis of the $Al_{15}(FeMn)_3Si_2$ shows Fig. 8. The left hand side's picture shows 3D morphology of structural parameters and the right hand side's picture shows the mapping microanalysis (the area concentration of the alloying elements in microstructure).

The line analysis of $Al_{15}(FeMnCr)_3Si_2$ phase shows Fig. 9. The analysis shows confrontation of alloying elements along the green line shown in the bottom picture. It can be seen, that in the phases are Fe, Mn, Cr, Si and Al elements.

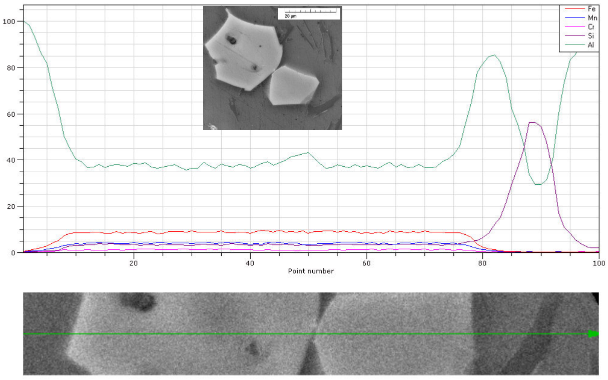


Fig. 9 The $Al_{15}(FeMnCr)_3Si_2$ identification using phase line EDX analysis, etch. 0.5 % HF

IV. CONCLUSION

The metallographic studies of secondary A226 cast aluminium alloys are very important, because metal quality is for control and prediction of casting characteristics necessities. The results of optical and scanning electron microscope studies of recycled A226 cast alloys are summarized as follows:

The secondary cast alloys used in this study possessed a complex as-cast microstructure. By using various instruments (light microscopy, SEM) and techniques (black-white and deep etching, EDX analysis) a wide range of structural parameters were observed. The microstructural analyses show that all of the structure parameters occurring in primary A226 microstructure were observed in microstructure of secondary A226 alloy, too. Moreover, in the microstructure were observed the other structure parameters, which cause decreasing properties of secondary aluminium alloy.

This study shows that mechanical properties of secondary A226 cast alloy are lower in comparison with mechanical properties of primary A226 cast, but this material was not modified, grain refined or heat treated for properties improvement.

The results of the study is: it is not easy to use the some marked secondary aluminium alloys in industries application, besides previous microstructure and mechanical properties study, because only small changes of addition elements causes the formation of different intermetallic phases in structure and causes decreasing of properties. Therefore is necessary the metallographic control of secondary Al-Si cast alloys.

ACKNOWLEDGMENT

The authors acknowledge the financial support of the projects VEGA No 1/0533/15 and European Union - the Project ITMS 26110230117.

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