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CORRELATION BETWEEN MACROSEGREGATION AND MECHANICAL PROPERTIES IN EN AW-6060 ALUMINIUM ALLOY BILLETS OBTAINED BY CONTINUOUS CASTING

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Modern non-ferrous metal applications are faced to high requirements in terms of even distribution of the alloying elements. In general, the homogeneity of the chemical composition of the materials affect to their mechanical properties. As part of this paper the relationship between the local concentration of Mg and Si in 90 mm diameter billets from EN AW-6060 aluminium alloy and local variability of yield stress in experimental conditions which simulates technological conditions for hot metal forming processes. The phenomenon of macrosegregation remained specified for billets obtained in the technology of horizontal continuous casting, dedicated to extrusion or forging.

Keywords: aluminum alloy, continuous casting, billet, macrosegregation, mechanical properties

INTRODUCTION

In industrial practice billets/ingots from aluminium alloys dedicated to metal forming are commonly produce by vertical, semi-continuous casting – Direct Chill Casting (DCC). There is also possibility to obtain these types of materials by horizontal continuous / semi-continuous casting. This method allows to obtain smaller diameters and longer process length of casts. Each of these methods generates different segregation pattern of chemical elements in the micro- and macro- scale. Microsegregation, identified with the variation in chemical composition within grain, it can be removed as a result of diffusion processes (e.g. during homogenization) [1-5].

Macrosegregation (macro- scale chemical composition variation within cast) is much more dangerous because of low solid-state diffusion coefficient of solute dissolved in matrix makes macrosegregation effects impossible to eliminate by heat treatment of the cast. Counteracting undesirable effects of macrosegregation is therefore related to the stage preceding the transition from the liquid to the solid state of the material, which is correlated with the way of liquid metal dosing into the solidification zone, control of the solidification conditions of the material, sequence of metal movement in primary cooling zone and morphology of phases. Mechanisms that control distribution of chemical elements are correlated with movement of the liquid and solid metal fractions in close proximity of solidification front during continuous and semi-continuous casting. Thermal factor, concentration gradient, metallostatic pressure, casting shrinkage and gravity are the main driving forces of these movements. The distribution of chemical elements on the macro- scale is strictly correlated with partition coefficient defined as proportion of chemical element concentration in the solid and in the liquid phase. Macrosegregation with maximum of chemical element concentration near the billet center is characterized by the partition coefficient higher than 1. While partition coefficient below 1, the solute enriched subsurface area of the billet. The extreme dispersion of chemical elements in the material is greater than value of the partition coefficient deviates more from 1. As a consequence, this state of affairs is responsible for anisotropy of mechanical properties in the volume of casting billet [6-8].

EXPERIMENTAL PROCEDURE

The research material was obtained in horizontal continuous casting line under various process parameters (feed steps, stop time, cooling conditions). EN AW-6060 aluminium alloy ϕ 90 mm billets (acc. EN 573-3:2009 standard chemical composition) was obtained as a result of metallurgical synthesis of aluminum and certified metallurgical master alloys. Process parameters selection during castings give a different deviation of chemical elements – high (approx. 15 % wt.) and low (under 5 % wt. macrosegregation, i.e. differentiation of chemical element concentration in the billet in relation to the average value. Additionally, for high macrosegregation variant, homogenization process was carried out (600 °C, 100 h). The verification of the macrosegregation rate was carried out by measuring chemical composition by optical emis-

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sion spectroscopy analyzer Foundry Master Xpert. Measurements were made over the length of 1 meter billet, by averaging the measurements along its axis. The next step was turning normative samples from areas 1-7 for the high temperature tensile test. The mechanical properties were carried out on Galdabini 10 kN tensile machine (equipped with heating element) at 550 °C, with a constant strain rate (0,01 s $^{-1}$) Figures 1,2.

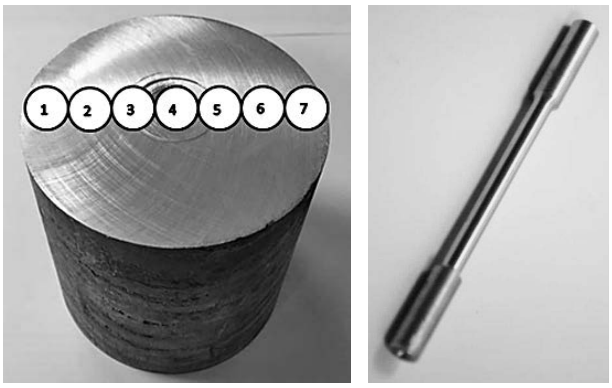

Figure 1 Schematic illustration of the sampling and an exemplary tensile test sample

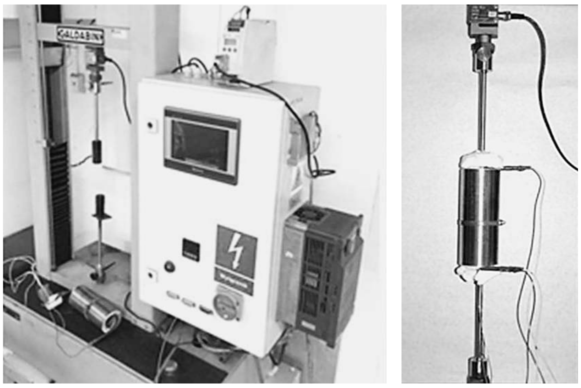

Figure 2 Galdabini tensile machine and the sample equipped with heating element

During hot tensile test the measured force was related to the actual cross-section of the sample (estimated from the constant volume rule) into form of true stress σ - true strain ε. In the engineering sense, the constant value of σ in the range of uniform deformations (between initial plastic strain and the moment until the neck) was defined as the average yield stress of the material.

RESULTS AND DISCUSSION

Table 1 presents the tensile test results: average yield stress, total elongation and the standard deviations. Figures 3 - 5 show the effects of macrosegregation and homogenization on billet mechanical properties variability.

Based on obtained research results, it was observed that the level of macrosegregation influences the mechanical properties. Moreover, the Si macrosegregation is higher than Mg and depends on casting conditions. The curves show the asymmetric distribution of Mg and Si concentration with respect to the axis of the billet on its diameter (no distinct extreme in axis). In the subsurface area of billets depletion in Si and enrichment in Mg was observed. The local concentration of Mg and Si was, generally similarly opposite in the significant areas of the billet. Approximately, the minimum Si concen-

Table 1 **Summary of tensile test results 550 °C**

MACROSEGREGATION RATE	LOW	HIGH	HIGH
Homogenization	–	–	–
Yield stress avg./MPa	10,9	10,5	9,2
St. deviation of yield stress/–	0,6	1,3	0,75
Total elongation avg./%	30	24	38
St. deviation of total elongation/–	5	11	8

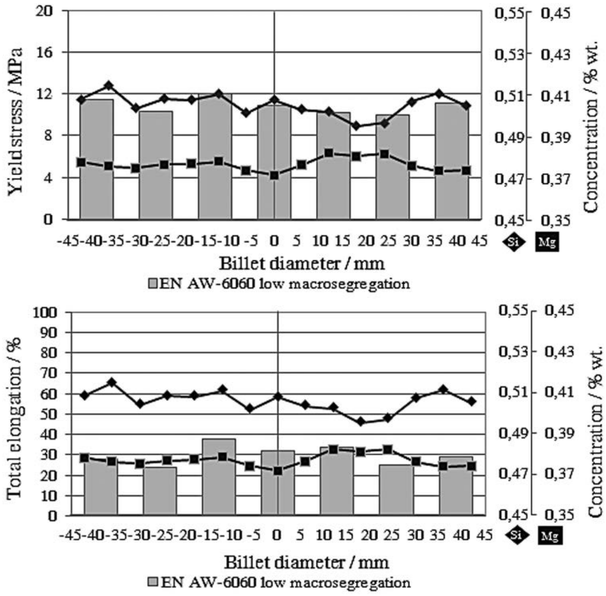

Figure 3 Mechanical properties as a function of Si and Mg concentration for EN AW-6060 (10 mm feed step / 10 s stop time / cooling 15 l / min) – low macrosegregation

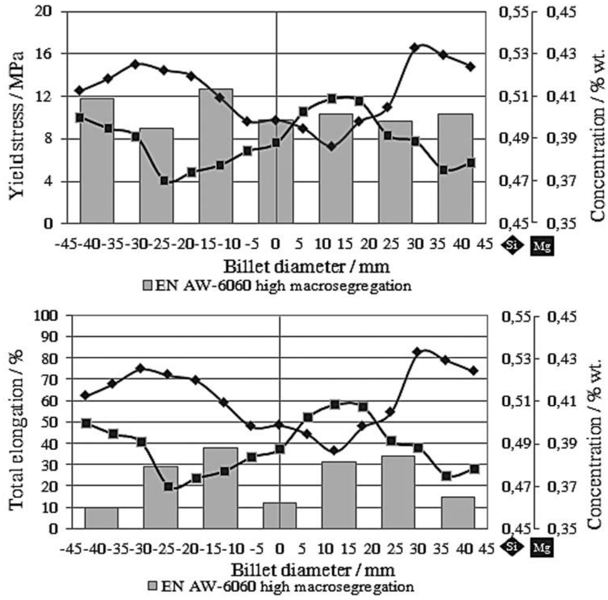

Figure 4 Mechanical properties as a function of Si and Mg concentration for EN AW-6060 (40 mm feed step / 10 s stop time / cooling 25 l / min) – high macrosegregation

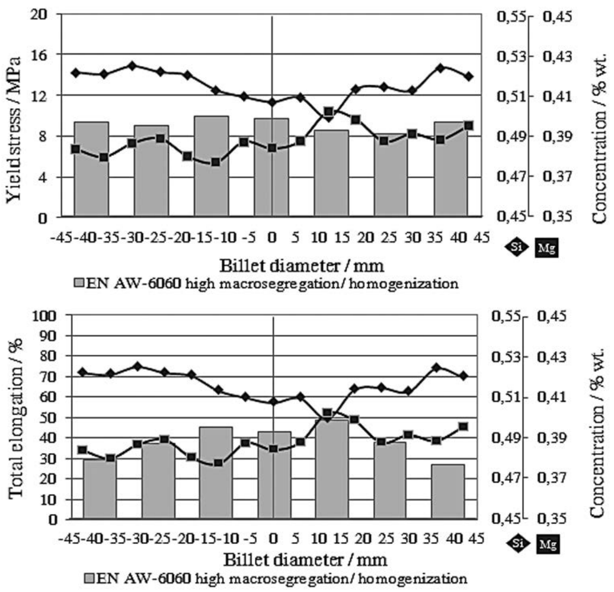

Figure 5 Mechanical properties as a function of Si and Mg concentration for homogenized EN AW-6060 – high macrosegregation

tration and the maximum Mg concentration are located in the same significant area of the billet. It is difficult to carried out a quantitative analysis of the influence of local Mg and Si concentration on mechanical properties. The obtained results are relatively correlated with literature knowledge [9].

In general, the level of average yield stress and elongation for low and high macrosegregation is similar, i.e. approx. 10 MPa yield stress and 25 – 30 % total elongation. However, the anisotropy of both characteristic is more than 50 % lower in the low macrosegregation variant. Homogenization process resulted in a yield stress decrease by 12 %, with a significant elongation increase by 38 %. The anisotropy of mechanical properties was significantly reduced, i.e. by approx. 40 % for yield stress and approx. 30 % for total elongation. Referring to the test results of homogenized variant to low macrosegregation variant, a decrease in yield stress by 16 % and an increase in total elongation by 21 % were recorded.

CONCLUSONS

In summary, it is postulated that Mg and Si macrosegregation rate indicates anisotropy of mechanical properties in tested billets. Generally, the phenomenon of Si and Mg macrosegregation in EN AW-6060 aluminium alloy billets is elaborate. Magnesium shows negative segregation in subsurface areas and positive segregation in the middle, while silicon showing positive segregation in subsurface areas and negative segregation in the middle. In practical point of view, high macrosegregation rate constitute a risk of defects formation during hot metal forming processes. The application of material with variable yield stress into the plastic deformation zone causes the appearance of areas privileged for earlier plasticization (lower mechanical properties). In addition, the presence of areas of significantly lower ductility can generate cracks during extrusion or forging processes. Homogenization process reduces the anisotropy of mechanical properties, but does not provide to complete homogenization material properties. The asymmetry of the Mg and Si concentration curves in relation to the axis of the billet results from the gravity force interaction during the horizontal continuous casting process.

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