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# INFLUENCE OF HEAT TREATMENT ON MECHANICAL PROPERTIES OF ALUMINIUM ALLOY EN AW-2011

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**Abstract**

*The EN AW-2011 alloy is semi-continuously cast into billets, which are extruded into semi-finished products such as bars, tubes, and wires, and are further processed into final products for the following applications: screw machine products, application parts and equipment, weaponry, the automotive industry, electronics, hardware, and machine parts. For precipitation hardening alloys, heat treatment is just as important as forming. Homogenization, which is carried out before extrusion, and aging, which takes place after extrusion, represent the important parts of the research questions in the field of industrial energy and economy. The optimization of time- and temperature-efficient heat treatments represents a challenge for research and scientific institutions that contributes to the further development of the metallurgical profession and industrial plants. Despite possible changes, the end products must have an appropriate microstructure and mechanical properties.*

*The heat treatment (homogenization) was carried out on samples from vertically semi-continuously cast billets made from EN AW-2011 alloy at a temperature of 520 °C and over 8 different time periods. Differential scanning calorimetry was carried out to define and confirm the success and suitability of the experimental heat treatment. Based on these results, optimal homogenization parameters were selected for further investigations. This was followed by artificial aging that included two different aging temperatures and correspondingly adapted time intervals.*

*The most optimal homogenization was selected at 520 °C for 4 hours and artificial aging at 170 °C for 14 hours.*

**Keywords:** *Alloy EN AW-2011, heat treatment, homogenization, artificial ageing, mechanical properties*

## 1. INTRODUCTION

The aluminium alloys of the 2xxx series, based on the Al-Cu system, have high strength and low specific weight, which ensures the wide use of extruded products made of such alloys for structural components, especially for military applications. It is important to emphasize that these alloys have a low degree of deformation during extrusion, which requires high pressures during processing, resulting in a low extrusion factor [1, 2]. Alloy EN AW-2011 is cast semi-continuously into billets, which are extruded into semi-finished products such as bars, tubes and wires and further processed into finished products [3]. An important step in the manufacture of products from the alloy EN AW-2011 is homogenization, which achieves a rounded and more compact form of the eutectic phases [4-6], and aging, which causes the precipitation of copper-based precipitates [5, 7]. Copper contributes significantly to the strength properties of the alloy during aging [8-10].

## 2. EXPERIMENTAL

The experimental section was designed based on initial calculations with the Thermo-Calc software (TC) and the TCAL6 database using the actual chemical composition of the EN AW-2011 alloy samples and the results of the differential scanning calorimetry analysis (STA 449C

Jupiter, Netzsch). Based on these results, the homogenization of as-cast samples taken at D/4 of the billet at a constant temperature of 520 °C in a laboratory furnace (Bosio) for eight different times was performed. The results of the billets homogenized for different times were compared with the results of the analyzes using light microscopy (Zeiss Axio Observer 7), scanning electron microscopy (SEM, JEOL JSM 6610) and measured Brinell hardness (WICK ZHU 250CL). The samples for the investigation of the influence of homogenization and aging on the mechanical properties were taken from rods extruded on an indirect extruder and previously homogenized at 520 °C for 4, 5 and 6 hours. Aging was carried out at two different temperatures (170 °C and 190 °C) and ten different times (8, 9, 10, 11, 12, 13, 14, 15, 16 and 17 h). After determining the optimum temperature and time based on the hardness of the samples, the tensile tests (Zwick Roell, the samples were prepared according to the DIN 50125 – B 14 × 70 standard, and the tensile test was carried out according to the ISO 6892-1 standard) were performed only on selected samples.

## 3. RESULTS AND DISCUSION

Table 1 shows the chemical composition of the experimental alloy. Figure 1a illustrates the non-equilibrium solidification of the EN AW-2011 alloy according to the Scheil diagram. Solidification of the primary α-Al solid solution begins at 642.7 °C, followed by eutectics: α-Al + $Al_{13}Fe_4$ at 627.3 °C, α-Al + $Al_{13}Fe_4$ + Bi at 618.3 °C, α-Al + $Al_7Cu_2Fe$ + Bi at 594.5 °C, and finally α-Al + $Al_2Cu$ + Bi at 542.5 °C, which continues until the end of solidification at 519.0 °C. At this temperature, α-Al + β-Si + $Al_2Cu$ + Bi also appears. DSC heating (Fig.1b) showed precipitation at 267.8 °C (due to non-equilibrium solidification). Eutectic melting started at 542 °C (θ-$Al_2Cu$, solidus), followed by eutectic melting at 566 °C ($Al_7Cu_2Fe$), 619.8 °C ($Al_{13}Fe_4$) and finally at 633.5 °C (α-Al). Upon cooling, the liquidus appeared at 635 °C (according to TC at 642 °C), then the eutectic with $Al_7Cu_2Fe$ at 580 °C and the eutectic with θ-$Al_2Cu$ at 528 °C (according to TC).

*Table 1. Average chemical composition of alloy EN AW-2011*

| Element | Si | Fe | Cu | Mn | Mg | Ni | Ti | Pb | Sn | Bi | Al |
|---|---|---|---|---|---|---|---|---|---|---|---|
| wt/% | 0.15 | 0.45 | 5.44 | 0.01 | 0.007 | 0.006 | 0.006 | 0.31 | 0.002 | 0.52 | Ost. |

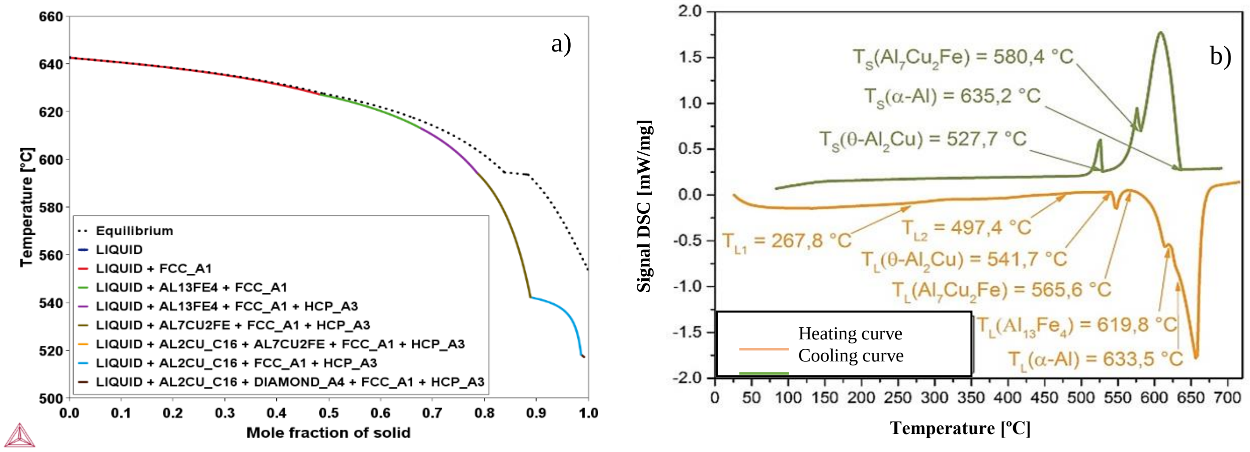



*Figure 1. Scheil diagram of non-equilibrium solidification of EN AW-2011 alloy according to TC calculations (a) and DSC heating and cooling curve for EN AW-2011 alloy (b)*

The hardness criterion 58 HB after homogenization at 520 °C was used to select the optimum homogenization method. All samples achieved a hardness of 60 HB, with a range between 60 HB and 90 HB (Fig.2a). The hardness increases with the homogenization time, reaches a maximum after four hours and starts to decrease with increasing time. Based on these results, homogenization at 520 °C for 4 hours, cooled in water, can be considered for the most optimal homogenization method. The decrease in hardness after a certain time is a consequence of the formation of the equilibrium phase θ [11, 12] whereby the hardness in the microstructure with a combination of the phases θ and θ' is the highest.

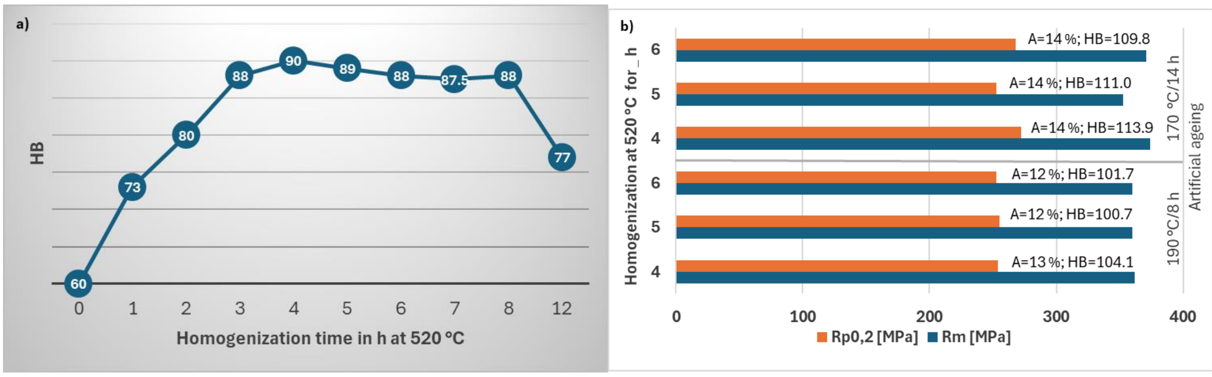



*Figure 2. Graphical representation of measured hardnesses for samples homogenized at 520 °C at different times, cooled in water (a) and results of mechanical properties for homogenized billets at 520 °C for 4, 5 or 6 h, extruded and artificial aged at 190 °C for 8 h or 170 °C for 14 h (b).*

The microstructure analysis (Fig.3) was intended to confirm the optimum homogenization regime that had already been predicted based on the measured hardness criteria. At a homogenization time of 4 h, the microstructure differs significantly from the as-cast microstructure, as the eutectic networks change from continuous to discontinuous during homogenization. Already after 4 h a more uniform distribution of eutectics between the grains was observed, but at the same time no larger, coarser Cu eutectics was detected. No major changes were observed for longer periods of time. In addition to the hardness of the material, the optimum homogenization regime at 520 °C for 4 h was also determined by analysing the microstructures.

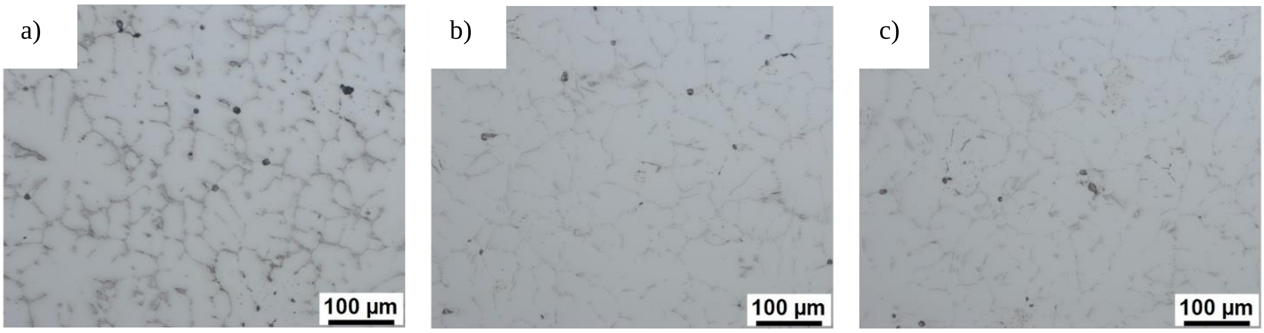
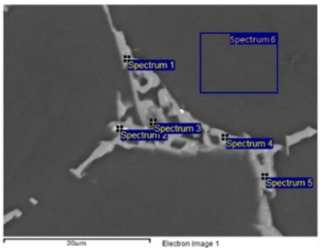



*Figure 3. Microstructural images of as-cast state (a) and after homogenization at 520 °C for 4 h (b) and 8 h (c), cooled in water*

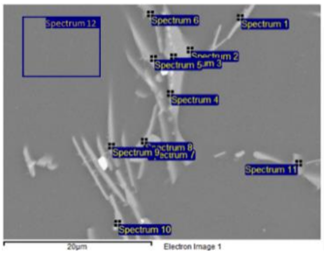
The results of the EDS analysis of the average value of several measurements are shown in Fig.4. In the cast sample, the copper content in the matrix is significantly lower than in the homogenized samples. Only one type of intermetallic eutectic phase was observed in the as-cast sample. A similar type of eutectic phase was observed in all other homogenized samples. In the homogenized samples, an additional acicular phase occurs in addition to the honeycomb eutectic phase. During the homogenization process, Cu increases in α-Al up to the maximum solubility of Cu. The process of dissolution of AlCuFe into AlCu takes place. Particles based on Bi and Pb remain unchanged during the homogenization process.

The billets were homogenized (4–6 hours at 520 °C), extruded and aged at 170 °C and 190 °C for different times. Tensile tests were only carried out on the samples that showed the most favorable properties, i.e. after 4, 5 and 6 hours of homogenization at 520 °C and 14 hours of aging at 170 °C and 8 hours of aging at 190 °C (Fig. 2b). A 4-hour homogenization followed by ageing at 170 °C/14 h resulted in the highest tensile properties achieving suitable hardness of 113.9 HB. The $R_m$ values analyzed were between 353 MPa and 374 MPa. Based on the measured $R_{p0.2}$ values of 268 MPa, the more favorable ageing behavior at a lower temperature (170 °C) and a longer time (14 h) can be determined.



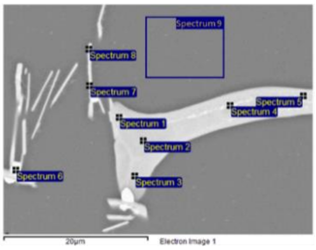
a)

| Spectrum | Al | Fe | Cu | Pb |
|---|---|---|---|---|
| Spectrum 1 | 53,88 | 7,2 | 38,92 | |
| Spectrum 2 | 37,59 | 6,46 | 21,72 | 34,23 |
| Spectrum 3 | 85,02 | | 14,98 | |
| Spectrum 4 | 54,62 | | 45,38 | |
| Spectrum 5 | 51,35 | 3,13 | 45,38 | |
| Spectrum 6 | 97,38 | | 2,61 | |



b)

| Spectrum | Al | Fe | Cu |
|---|---|---|---|
| Spectrum 1 | 68,66 | 5,00 | 26,34 |
| Spectrum 2 | 62,53 | 10,29 | 27,18 |
| Spectrum 3 | 51,92 | 10,93 | 37,15 |
| Spectrum 4 | 61,43 | 6,62 | 31,95 |
| Spectrum 5 | 67,13 | 8,47 | 24,40 |
| Spectrum 6 | 74,97 | 6,17 | 18,87 |
| Spectrum 7 | 45,10 | 2,15 | 52,74 |
| Spectrum 8 | 56,57 | 1,09 | 42,34 |
| Spectrum 9 | 69,67 | 7,18 | 23,15 |
| Spectrum 10 | 70,09 | 7,56 | 22,34 |
| Spectrum 11 | 73,39 | 6,89 | 19,72 |
| Spectrum 12 | 94,84 | | 4,99 |



c)

| Spectrum | Al | Fe | Cu | Bi |
|---|---|---|---|---|
| Spectrum 1 | 54,84 | 10,21 | 26,28 | 8,67 |
| Spectrum 2 | 62,44 | 10,49 | 27,07 | |
| Spectrum 3 | 61,18 | 10,70 | 28,12 | |
| Spectrum 4 | 53,56 | 12,92 | 33,51 | |
| Spectrum 5 | 54,70 | 13,29 | 32,01 | |
| Spectrum 6 | 22,20 | | 3,00 | 94,78 |
| Spectrum 7 | 70,37 | 7,56 | 22,07 | |
| Spectrum 8 | 71,31 | 7,51 | 21,18 | |
| Spectrum 9 | 94,37 | | 5,17 | |

*Figure 4. SEM SEI images with marked points and areas of EDS analysis of as-cast sample (a) and samples homogenized at 520 °C 4 h (b) and 8 h (c), cooled in water*

## 4. CONCLUSIONS

Thermodynamic calculations and DSC analysis confirmed the appropriateness of the choice of homogenization temperature of 520 °C. According to the results of the measured hardness, LM and SEM-EDS microstructural properties, the homogenization process at 520 °C is completed after 4 hours for the investigated alloy. The existing homogenization regime, 6 hours at 520 °C, can be optimized to only 4 hours at the same temperature.

The optimization of the reduction of the homogenization time consequently led to a change in the aging heat treatment regime. The best results in terms of mechanical properties were obtained when aging at 170 °C for 14 hours.

## ACKNOWLEDGEMENTS

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## REFERENCES

[1] Y. Birol, Mater. Chem. Phys., 131 (2012) 694-697.
[2] C.K.S. Moy, M.Weiss, J. Xia, G. Sha, S.P. Ringer, G. Ranzi, Mater. Sci. Eng. A., 552 (2012) 48-60.
[3] J.R. Davis, Aluminum and Aluminum Alloys, Ohio: ASM International, 2001, p.65
[4] S-M. Liang, R. Schmid-Fetzer, CALPHAD: Comput. Coupling Phase Diagrams Thermochem., 51 (2015) 252-260.
[5] O. Zobac, A. Kroupa, A. Zemanova, K.W. Richter, Metall. Mater. Trans. A., 50A (2019) 3805-3815.
[6] M. Vončina, I. Paulin, A. Debevec, A. Nagode, Mater. Tech., 55 (2021) 327-333.
[7] J-H. Jang, D-G. Nam, Y-H. Park, I-M. Park, Trans. Nonferrous Met. Soc. China, 23 (2013) 631-635.
[8] C. Vargel, Corrosion of Aluminium: Second Edition. Oxford: Elsevier, 2019, p.858.
[9] S. SAMARAS, G.N. Hademenopoulos, Conference: 1st International Conference on Manufacturing Engineering, Halkidiki, Grece, 2002.
[10] D. Mirković, J. Gröbner, I. Kaban, W. Hoyer, R. Schmid-Fetzer, Int. J. Mater. Res., 100 (2009) 176-188.
[11] D.J. Chakrabarti, D.E. Laughlin, Prog. Mater. Sci., 49 (2004) 389-410.
[12] M. Vončina, A. Nagode, J. Medved, I. Paulin, B. Žužek, T. Balaško, Metals, 11 (2021) 1211.