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THE INFLUENCE OF CHEMICAL COMPOSITION AND HEAT TREATMENT ON THE MECHANICAL PROPERTIES AND WORKABILITY OF THE ALUMINIUM ALLOY EN AW 5454

VPLIV KEMIJSKE SESTAVE IN TOPLOTNE OBDELAVE NA MEHANSKE LASTNOSTI IN PREOBLIKOVALNOST ALUMINIJEVE ZLITINE EN AW 5454

Alenka Šalej Lah[1*], Jožef Medved[1], Peter Fajfar[1], Irena Paulin[2], Darja Volšak[3], Maja Vončina[1]

[1]Department for Materials and Metallurgy, Faculty of Natural Sciences and Engineering, University of Ljubljana, Aškerčeva 12, Ljubljana, Slovenia
[2]Institute of Metals and Technology, Lepi pot 11, Ljubljana, Slovenia
[3]Impol FT d.o.o., Partizanska 38, 2310 Slovenska Bistrica, Slovenia

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The influence of chemical composition and heat treatment on the mechanical properties and formability of the selected commercial aluminium alloy EN AW 5454 was investigated. The main properties of the Al alloy 5454 from the AA 5xxx series are very good corrosion resistant and good formability. From a cast slab a 50-mm-thick slice was taken from the width cross-section in the slab centre. One half of the slice was homogenised for 10 h at a temperature of 530 °C. The cast and homogenised samples were investigated using light and scanning electron microscopy. For the study of the influence of the heat treatment, samples in the as-cast state were annealed in a laboratory furnace at a temperature of 530 °C for (4; 6; 8; 10; 12) h. To study the influence of the chemical composition, four different samples were prepared: the first without additions, the second with an addition of 1 *w*/% Mn, the third with 3 *w*/% Mg and the fourth with an addition of both elements, Mn and Mg. The XRF analyses confirmed the desired chemical composition of all four alloys produced. Half of each alloy sample was homogenised at the same temperature and time as the base alloy in the as-cast state. The hot-deformation behaviour of the different alloys was investigated using cylindrical hot compression tests performed on a Gleeble 1500D thermo-mechanical simulator. By comparing the flow curves a strong influence of the thermo-mechanical parameters on the alloy formability can be seen. The alloy has good workability and with the addition of Mn and Mg, the stress values are higher than those of the base alloy.

Keywords: aluminium alloys, EN AW 5454, chemical composition, heat treatment, hot compression test

Povzetek: V članku je opisana raziskava vpliva kemijske sestave in toplotne obdelave na mehanske lastnosti in preoblikovalnost izbrane komercialne aluminijeve zlitine EN AW 5454. Glavne lastnosti zlitine 5454 iz serije AA 5xxx so zelo dobra odpornost proti koroziji in sposobnost preoblikovanja. Iz sredine ulitega bloka je bila izrezana rezina debeline 50 mm. Polovica rezine je bila 10 ur homogenizirana pri temperaturi 530 °C. Vzorci v litem in homogeniziranem stanju so bili pregledani z uporabo optične in elektronske mikroskopije. Za preučevanje vpliva toplotne obdelave so bili vzorci v litem stanju žarjeni v laboratorijski peči pri temperaturi 530 °C in času (6; 8; 10; 12) ur. Za ugotavljanje vpliva kemijske sestave so bili pripravljeni štirje različni vzorci: prvi brez dodatkov, drugi z dodatkom 1 *w*/% Mn, tretji s 3 *w*/% Mg in četrti z dodatkom obeh elementov, Mn in Mg. Analize z rentgensko fluorescenco (XRF) so potrdile željeno kemijsko sestavo vseh štirih izdelanih zlitin. Polovica vsakega vzorca zlitine je bila homogenizirana pri enaki temperaturi in času kot osnovna zlitina. Opravljena je bila tudi analiza vpliva preoblikovalnosti v vročem za vse štiri zlitine s preizkusi vročega stiskanja, ki so bili izvedeni na termo-mehanskem simulatorju Gleeble 1500D. S primerjavo dobljenih krivulj tečenja lahko opazimo velik vpliv termo-mehanskih parametrov na preoblikovalnost zlitine. Zlitina ima dobro preoblikovalnost in z dodatkom Mg in Mn so vrednosti napetosti višje kot pri osnovni zlitini.

Ključne besede: aluminijeve zlitine, EN AW 5454, kemijska sestava, toplotna obdelava, tlačni test v vročem

1 INTODUCTION

Aluminium (Al) and magnesium (Mg) are two very important lightweight metals used in applications to reduce product weight, which is very important for the lifecycle assessment (LCA) of the product with which environmental performance can be improved.[1] In the automotive sector, light metals such as Al and Mg, have been used to produce lightweight vehicles and according to some studies, reducing the weight of the vehicles implies a reduction in fuel consumption between 0.1 L/(100 km × 100 kg) and 0.9 L/(100 km × 100 kg).[2] Pure Al is very soft and virtually all technical applications where aluminium is used, require higher strength. Mg alloys have great potential due to their low density and high strength.[3,4] Excellent properties of metals, are effective in exploiting mechanical properties such as strength, ductility, fatigue and fracture.[4] In AA 5xxx series Al alloys, additions of up to 6 *w*/% Mg lead to solid-solution hardening in combination with efficient strain hardening, which is why AA 5xxx series alloys are among the strongest non-age-hardenable Al alloys retaining very good

*Corresponding author's e-mail:
alenka.salej@omm.ntf.uni-lj.si

formability.[5,6] The Al alloy EN AW 5454 (AlMg3Mn) consists of Al, and Mg and Mn as the main alloying elements. The two main advantages of Mn additions are that the precipitation of the Mg phase is more general throughout the microstructure and that for a given increase in strength, Mn allows a lower Mg content and gives the alloy greater stability.[7] In addition to medium-to-high strength and good formability, the main properties of the Al-Mg alloy EN AW 5454 are its very good corrosion resistance, especially to seawater, and the general environmental conditions as well as excellent weldability.[8] The main method of forming alloys of this series is hot plastic deformation (HPD), such as forging, rolling, extrusion, pressing, which makes it possible to obtain products of a relatively complex shape for use in various industries. Typical applications of the EN AW 5454 alloy, which is usually in the form of plates, sheets, rods, wires and tubes, therefore include road transport, chemical processing and food processing plants, aerospace, pressure vessels, containers, boilers, marine and offshore industries, pylons and masts. These alloys do not undergo strengthening by heat treatment because they are strengthened by Mg, and each percentage of Mg increases the strength of the Al by about 30 MPa.[9,10]

The process route for the selected alloy involves direct chill (DC) casting, followed by a homogenisation heat treatment, and the alloy is then hot rolled, usually in the temperature range up to 500 °C, followed by cooling to room temperature within 24–48 h.[11] Thus, for a given composition, the thermo-mechanical processing history of the alloy controls the microstructure and the resulting properties of the product when it is delivered to the customer.[12] The thermo-mechanical behaviour of Al-Mg alloys under quasi-static load shows a positive strain rate sensitivity at higher temperatures in the same strain-rate range. A further advantage of warm-forming processes of aluminium alloys is that high temperatures influence the stress state in the obtained parts and thus reduce the spring-back effects.[13]

The aim of the paper is to show the influence of the chemical composition and heat treatment on the mechanical properties and the workability of Al alloy EN AW 5454. Metallographic specimens and samples in the form of a cylinder for hot-compression tests on the simulator for thermo-mechanical metallurgical states GLEEBLE 1500D were prepared. In the experimental part the chemical composition and metallographic analyses with the single-stage solution heat treatment are presented, followed by casting of the Al alloy with different chemical compositions. As known from the literature, these alloys are strengthened mainly by Mg, which is presented mainly in solid-solution form and by the addition of manganese.[9] The increasing proportion increases the strength of the aluminium. Since a higher Mg content greatly reduces the corrosion resistance of the alloys and leads to stress corrosion cracking, the Mg was only slightly increased. The mechanical properties of Al alloys containing Mg_2Si are also largely dependent on the morphology, size and distribution of the Mg_2Si phases, which are necessary to control and modify (heat treatment, etc.). Primary Mg_2Si and Chinese-script eutectic Mg_2Si can cause serious problems in the mechanical properties and become stress concentration points.[14] In addition, hot-compression tests were carried out on commercial and laboratory cast alloys with different chemical compositions.

2 EXPERIMENTAL PART

2.1 Chemical composition and metallographic analysis of the alloy EN AW 5454

From the cast slab of alloy EN AW 5454, which was produced on an industrial scale at the company Impol d.d., Slovenia, a 50-mm-thick slice in width cross-section was taken from the slab centre. One half of the slice was homogenized for 10 h at a temperature of 530 °C.

The composition of the alloy is given in **Table 1**.

Table 1: Maximum and minimum AA standard composition of the alloy EN AW 5454 (w/%)[13]

EN AW 5454	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti
max	0.25	0.40	0.10	1.00	3.00	0.20	0.25	0.20
min	0.08	0.17	0	0.50	2.40	0.05	0	0

A comparative analysis of the individual homogenised and as-cast samples was performed. The phase identification and microstructure characterization of the as-cast and homogenised samples were carried out using a light microscope (LM, Olympus BX61) and a scanning electron microscope (SEM JEOL 5610) equipped with an energy-dispersive X-ray spectrometer (EDS). The comparison of the microstructure of the inner as-cast sample 5454-29 and the homogenised sample 5454-4 was performed (**Figure 1**). To determine the thickness of the margin layer, the micrographs were assembled from different layers (Olympus BX61, LM).

2.2 The influence of heat treatment on the alloy EN AW 5454

To investigate the influence of the heat treatment on the selected alloy, samples of the as-cast part 2L were prepared and homogenised. Single-step solution heat treatments were carried out with an electric chamber furnace, which had been calibrated beforehand. The ho-

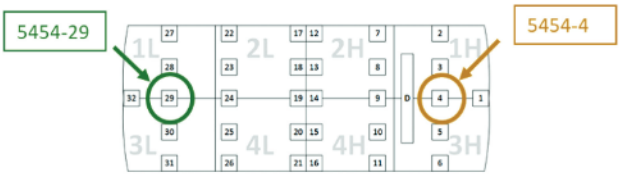

Figure 1: Scheme of the position of the as-cast sample 5454-29 and homogenized sample 5454-4 from the slice of the slab

mogenization was controlled with thermocouples to measure the temperature of the sample in the furnace. The homogenization was performed for (4; 6; 8; 10; 12) h at a temperature of 530 °C (**Table 2**). After the heat treatment, all the samples were quenched in water. The samples were then examined with a LM Olympus BX61.

Table 2: Duration of the homogenisation of the samples

Sample Name	S1	S2	S3	S4	S5	S6
Time	12 h	10 h	8 h	6 h	4 h	0 h

2.3 Casting aluminium alloy with different chemical compositions and compression tests

To investigate the influence of the chemical composition on the mechanical properties and formability, four different Al alloys with different additions of Mg and Mn were proposed. The commercial alloy EN AW 5454 was melted in an electric induction furnace and cast in the laboratory in the form of 22 mm × 150 mm rods.

Sample 1H was cast without additions, for sample 2H, 1 *w*/% Mn was added, for sample 3H, 3 *w*/% Mg was added and for sample 4H, both Mn (1 *w*/%) and Mg (3 *w*/%) were added. All four samples were homogenized at 530 °C for 10 h and quenched in water.

The characterisation of alloy samples 1H, 2H, 3H and 4H under hot-forming conditions was also carried out. For the compression tests on a simulator for the thermomechanical metallurgical states GLEEBLE 1500D+ the cylindrical samples from the homogenized part of the block (alloy EN AW 5454) and from all four homogenized laboratory samples of Al alloy EN AW-5454 were prepared. Samples were a cylindrical shape with a diameter of 10 mm and a length of 15 mm.

Compression tests were performed to determine the behaviour of the materials during plastic deformation. The compression tests were performed at two different temperatures, 350 °C and 450 °C, with the same strain rate of 1 s^{-1} and strain 1.

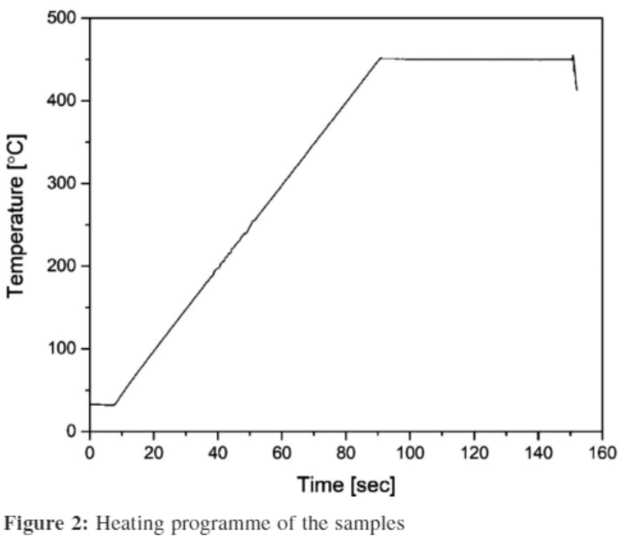

Figure 2: Heating programme of the samples

Based on the hot-rolling plan for the alloy EN AW 5454, which was given by Impol d.d., a test plan to determine the formability in hot-rolling process of the selected alloy was made. The heating rate to the deformation temperature was 5 °C/s, the holding time at the deformation temperature was 60 s, followed by water cooling of the sample after deformation (**Figure 2**).

3 RESULTS AND DISCUSSION

3.1 Microstructure

Based on the literature[8,15,16] and the performed analyses, eutectic phases Mg_2Si, the dark phases, and the bright intermetallic phase $Al_6(Mn,Fe)$ can be observed on the micrographs of the cast sample 5454-29 (**Figure 3**). X. Zhu et al.[15] showed that the $Al_6(Mn,Fe)$ phase has a different morphology and size, which is a consequence of the Fe content. The phase can be identified as a primary (blocky morphology, rhombic with a hollow), divorced eutectic (needle and small rhombus), regular eutectic morphology with a curved plane and sometimes also exhibits a Chinese-script structure.[16,17] On the micrographs from the centre of the slice (5454-29, 5454-4) the eutectic $Al_6(Mn,Fe)$ phases can be observed. **Figure 4** shows the samples from the edge of the slice in the as-cast state (5454-32) and after homogenization sample (5454-1) where the primary rhombic phases with a hollow can be identified. The silicon phase is less common in the homogenized samples, which means that the Mg_2Si constituents were dissolved at a temperature of 530 °C.

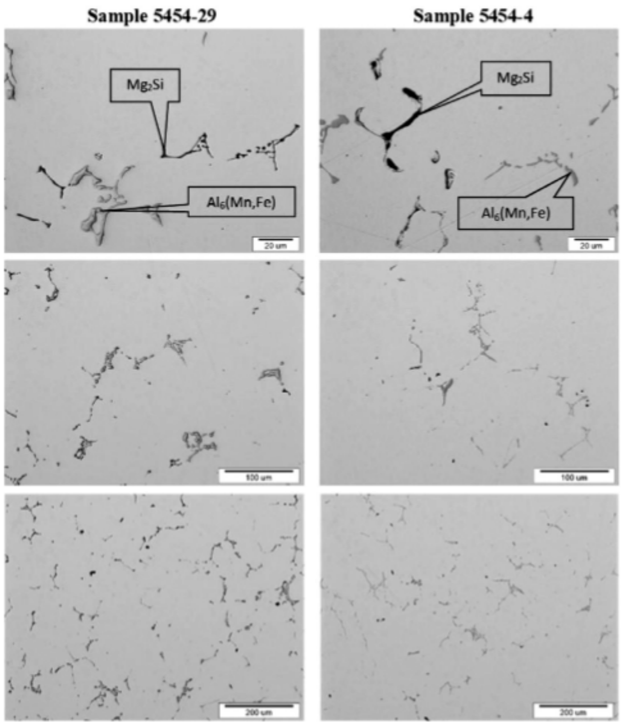

Figure 3: Microstructure of the alloy EN AW 5454 of the as-cast sample 5454-29 and homogenised 5454-4 at different magnifications

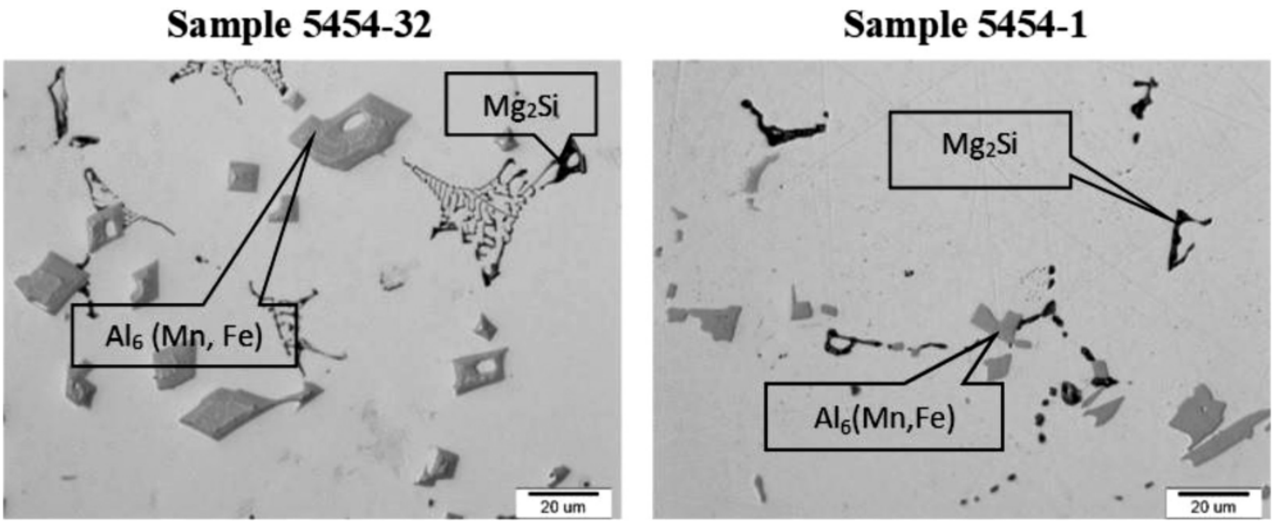

Figure 4: LM micrographs of the as-cast sample 5454-32 and homogenized sample 5454-1

The EDS analyses of sample 5454-29 (**Figure 5**, **Table 3**) and sample 5454-4 (**Figure 7**, **Table 4**) were performed to determine the type and phase composition in the as-cast and homogenized parts of the slice. From the EDS micrographs it can be observed that Cu accumulates in the centre of the Al_6(Mn,Fe) phase. Cu is visible inside or on the phase (bright layer), which was also detected by EDS line analysis of the sample in the as-cast sample, where the presence of Cu in the area of the bright spots from the micrographs is clearly visible (**Figure 6**). The primary Al_6(Fe,Mn) phase has inside hollows, while the eutectic phase is small and solid. After homogenization, the Cu phase in combination with the eutectic phase (AlFeMnSi) is no longer observed. During annealing the Cu gradually dissolves and disappears.

Intermetallic particles that appear grey in the SEM (**Figures 5** and **7**) seem to contain heavy elements such as Fe and Mn, while the phase containing light elements such as Mg and Si displays dark (in the form of Chinese script). EDS mapping has been employed on the as-cast sample 5454-32 to verify the chemical compositions of different phases (**Figure 8**). The majority of primary phases with blocky morphology, rhombic with a hollow

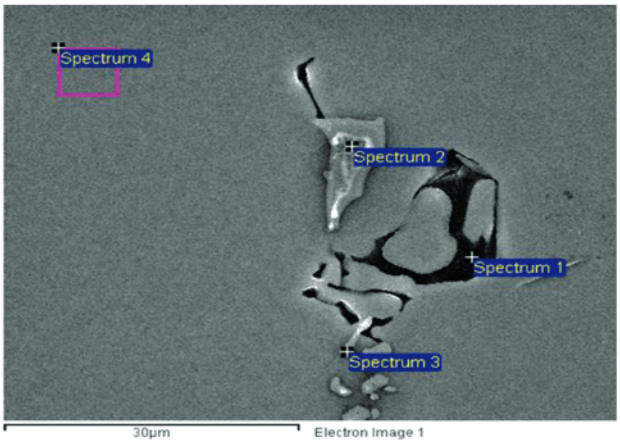

Figure 5: SEM micrograph with marked EDS analysis of as-cast sample 5454-29

Table 3: Chemical composition in mass fractions, (w/%) on denoted spots given in **Figure 5**

	Al	Mg	Mn	Si	Cu	Fe
Spectrum 1	bal.	4.0	–	8.8	–	–
Spectrum 2	bal.	–	8.4	4.4	13.1	16.6
Spectrum 3	bal.	2.3	2.9	–	24.5	7.8
Spectrum 4	bal.	–	–	2.8	–	–

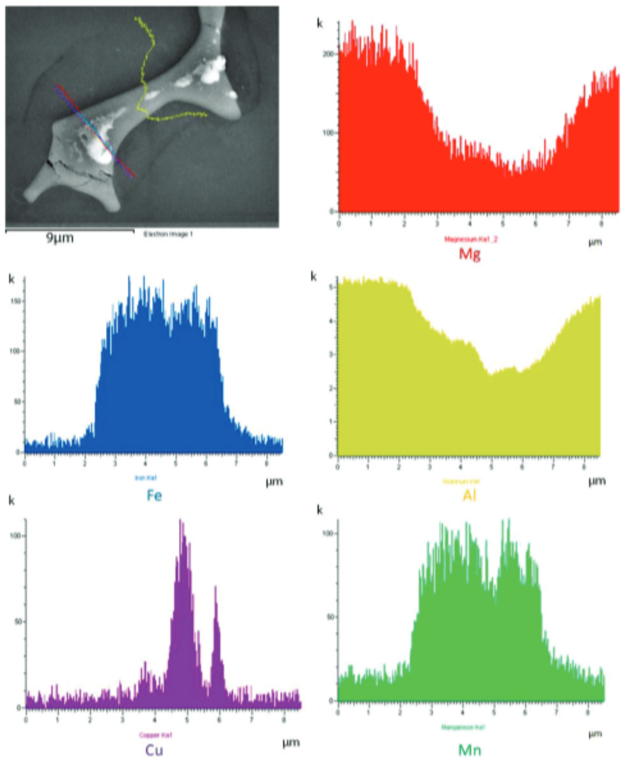

Figure 6: EDS line analyses through Al_6(Mn,Fe) regular eutectic phase of the as-cast alloy EN AW 5454

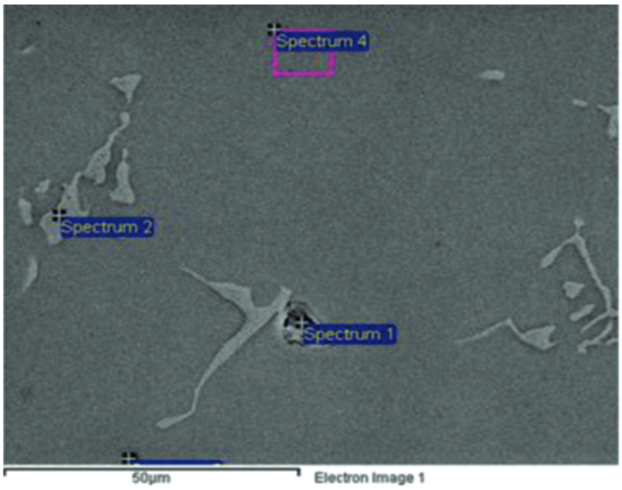

Figure 7: SEM micrograph with marker EDS analysis of homogenized sample 5454-4

Table 4: Chemical composition in mass fractions, (w/%) on denoted spots given in **Figure 7**

	Al	Mg	Mn	Si	O	Cu	Fe
Spectrum 1	bal.	2.5	–	1.3	7.5	–	–
Spectrum 2	bal.	–	9	5	–	–	19.4
Spectrum 4	bal.	–	–	2.5	–	–	–

are $Al_6(Mn,Fe)$, while the dark phase is identified as Mg_2Si.

The microstructure of the cast sample and the homogenized sample were imaged up to 1 cm deep from the edge into the interior of the sample (**Figure 9**). These two micrographs give a nice representation of the edge layers of the cast and homogenized slab. It can be observed that in the homogenized part of the slab the phases are more evenly distributed. In industry, the surface of the slab is ground down by 5 mm before homogenization, which is sufficient to remove the non-homogenized edge layer.

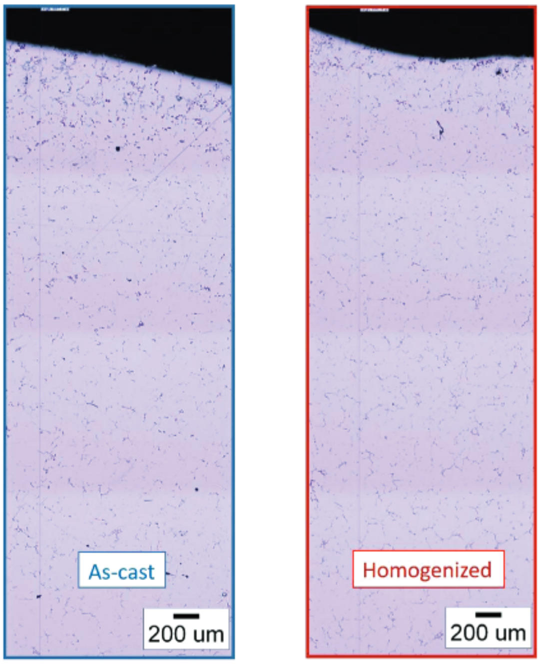

Figure 9: LM micrographs of as-cast and homogenized samples from the surface into the interior, depth of 10 mm

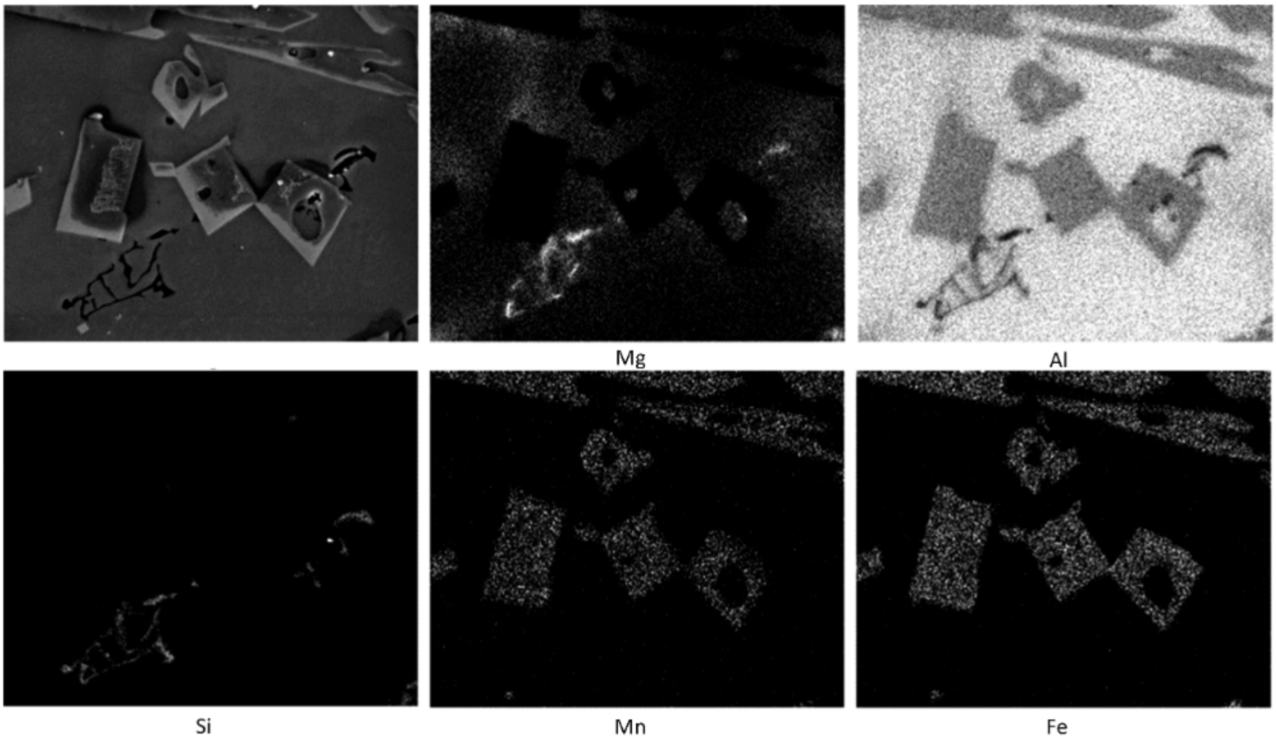

Figure 8: Mapping EDS analysis of the sample 5454- 32; Mg, Al, Si, Mn and Fe map

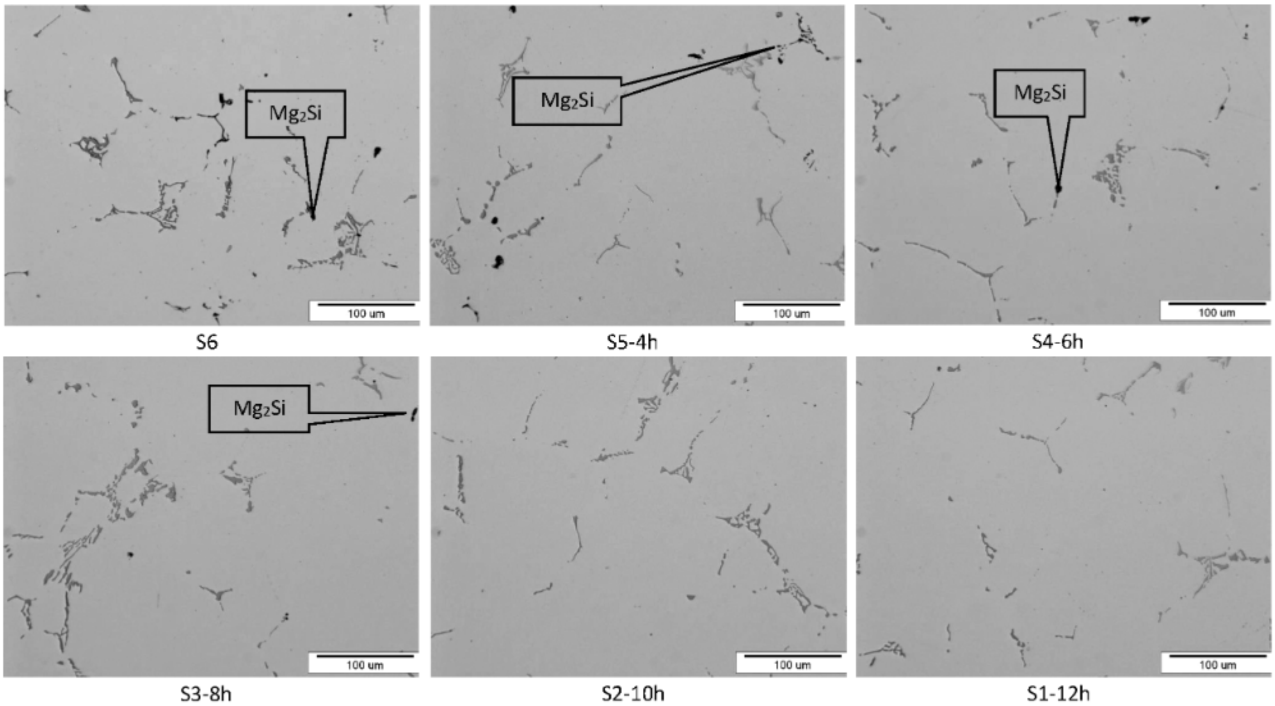

Figure 10: Micrographs of the samples in as-cast state and after homogenisation treatment after 4; 6; 8; 10 and 12 h

The LM micrographs taken from the samples according to different homogenization regimes (**Table 2**) are presented and show that the Mg_2Si phase dissolves with the longer homogenization. A large extent of Mg_2Si phase is dissolved, morphology changed from Chinese script to polygonal and the size of the phase decreased. This is evident in Figure 9 with less dark phases appearing due to the homogenization. With increasing time, less Al_6(Mn, Fe) phase is found in the samples, whereas the phases are smaller and more evenly distributed.

3.2 Flow stress behaviour

From the obtained true stress-true strain curves (**Figure 11**) it can be observed that the stress decreases with increasing temperature.

A rapid increase of stress at the early stages of straining due to work hardening is presented in all cases. In the case of the commercial alloy at the temperature of 450 °C the flow curve slightly decreases to the steady state after reaching the peak stress. At the temperature of 350 °C the steady state occurs after the flow curve reaches a maximum. The steady state is maintained by the process of dynamic softening. In the case of alloys with increased values of Mn and Mg (H2, H3, H4), the flow stress increases continuously, while the dynamic softening is inadequate to offset the work-hardening effect during hot deformation.

In the case of alloys with increased values of Mn (H2) and Mg (H3), it was found that the values of the maximum stress increased in comparison with the maximum stresses of the base alloy EN AW 5454. The stresses at the strain of 0.6 of the four samples tested at temperatures of 350 °C and 450 °C are shown in **Table 5**.

The stress-strain curves also show that the stress values of the alloys with added Mn (H2) and those with added Mn and Mg (H4) increased by the same amount, and in the alloy with added Mg (H3) the values were

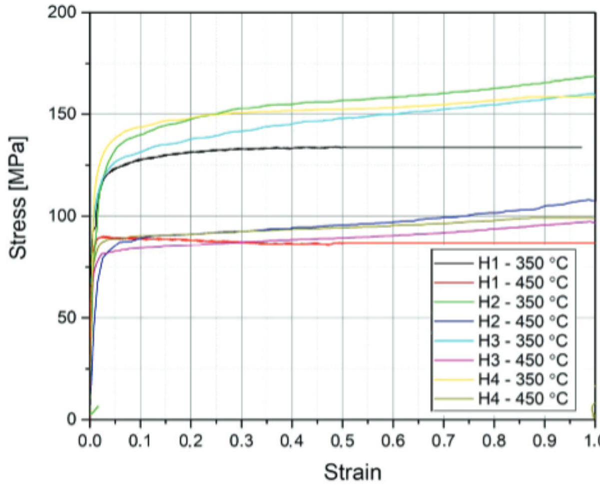

Figure 11: True stress-strain curves of the samples H1, H2, H3 and H4 at temperatures of 350 °C and 450 °C

Table 5: Stress at strain of 0.6

Temperature /°C	Stress/MPa			
	H1	H2	H3	H4
350	135	160	150	155
450	80	98	85	190

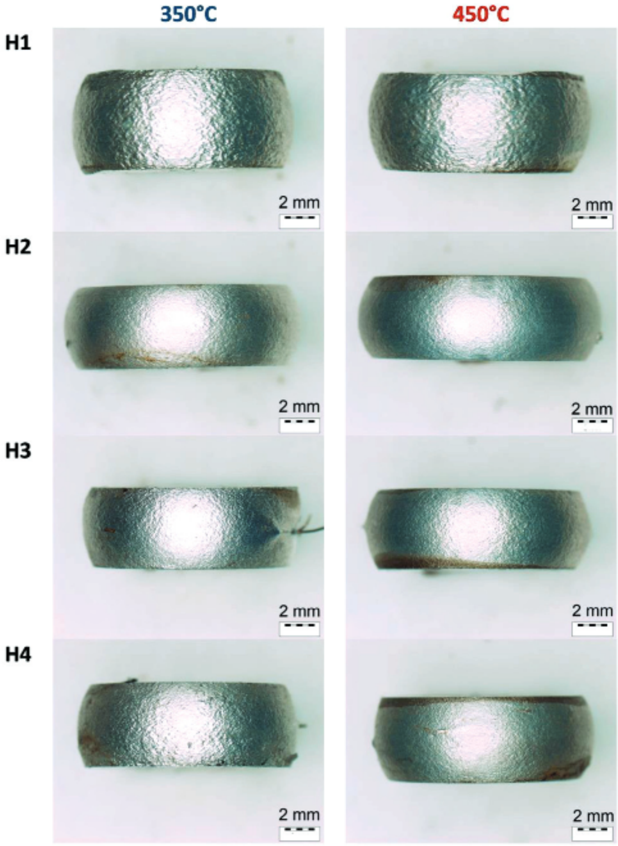

Figure 12: Macro photographs of the tested samples

only slightly higher than the values of the base alloy 5454. All the alloys have good workability under these forming conditions and no cracks or other defects were found on the macrographs of the test samples surfaces (**Figure 12**).

4 CONCLUSION

From the microstructure of the homogenised samples of the alloy EN AW 5454 it can be concluded that the Mg_2Si phase dissolves during homogenization and occurs less frequently in the homogenised samples. Also, the morphology of the phase is changed from Chinese script to a polygonal. After homogenization, less $Al_6(Mn,Fe)$ phase is observed, which is more finely distributed in the microstructure, and also the large phases seem to be shorter and rounder.

From the LM micrographs of samples after different homogenization regimes it can be seen that the Mg_2Si phase dissolves with the longer homogenization time. So we can conclude that at a temperature of 530 °C, homogenization can be effective enough after 8 h. With the increasing time, less $Al_6(Mn,Fe)$ phase is found and the phases are smaller and more evenly distributed.

The alloy has good workability, as no cracks or other defects were found on the deformed samples. With the addition of Mn and Mg, the stress values are higher than those of the base alloy.

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