New 6xxx Al–Mg–Si Alloy with High Electric Conductivity and Great Bendability for EV Applications

Gregor Michael, Josef Berneder, and Roland Lorenz

Abstract

In the past for current-conducting components copper was primarily used. Due to high material price and limited availability of copper, aluminum appears as a great alternative, especially since a higher weight-specific electrical conductivity is achievable and the lightweight construction is optimized. Excellent processing properties make this newest Al–Mg–Si alloy more than just a cheap alternative. Within the product development of the new 6xxx Al–Mg–Si alloy with high electric conductivity, the alloying elements and their solution state played key roles in reducing electrical resistance. Additionally, very good processing properties can be achieved, whereby the material required a specific strength and still has good bendability. During the production process, these properties were generated via a new solution heat treatment approach and subsequent over-aging. Results showed the new aluminum grade achieves an electrical conductivity of 58%IACS (International Annealed Copper Standard) and a crack-free 180° bend according to ASTM E290 (bending factor N = 1). Therefore, this aluminum alloy is ideal for use as a bus bar in EV batteries or other current-conducting applications such as EV charging stations.

Keywords

Aluminum alloys • 6xxx • Al–Si–Mg • Over-aging • High conductivity • E-mobility • Bus bar

G. Michael (✉) · J. Berneder · R. Lorenz
AMAG Rolling GmbH, Lamprechtshausenerstrasse 61, 5282 Ranshofen, Austria
e-mail: gregor.a.michael@amag.at

Introduction

The automotive industry is in the generational challenge to transition towards electromobility. In this context, there is still great potential in the development of new and improved materials that can be used for new applications in vehicle construction, especially in battery components. An important module is electrical conductors—mostly known as bus bars—for the time-dependent flow of electricity. Based on the high specific conductivity, low coefficient of linear thermal expansion, and resistance to corrosion, copper has historically established itself as the material of choice for current-carrying applications. However, regarding lightweight construction interests and from a commercial point of view, with continuous improvement aluminum offers a better alternative [1].

With a density of 8.96 g/cm^3, copper has a density that is more than three times higher than that of aluminum at 2.70 g/cm^3 [2]. At the same time, as of August 2023, the metal price per weight unit of copper is almost four times higher than aluminum, which is why great cost and weight savings can be generated despite the disadvantage of lower electrical conductivity [3]. Aluminum conductors require slightly greater cross-sections than copper conductors to ensure the same electric current-carrying capacity. Although pure 1xxx aluminum alloys have higher electrical conductivity, they are usually too soft for the requirements within this special application, whereby these alloys would require a higher proportion of primary aluminum with a higher CO_2-footprint due to their purity, which must always be considered in analysis for new product developments [4]. Another important factor for bus bar applications is the processability and good bendability to save space in the compact battery composite. Aluminum has an advantage over copper due to a better strength-to-weight ratio in 6xxx Al–Mg–Si alloys [5].

The strength-increasing mechanism in 6xxx Al–Mg–Si primarily relies on the formation of Mg_2Si-precipitations and their intermediate stages. Precipitations impede the sliding

S. Wagstaff (ed.), *Light Metals 2024*, The Minerals, Metals & Materials Series,
https://doi.org/10.1007/978-3-031-50308-5_16

Table 1 Chemical composition of EN AW-6101

	Si [wt. %]	Fe [wt. %]	Cu [wt. %]	Mn [wt. %]	Mg [wt. %]	Cr [wt. %]	Zn [wt. %]	Al [wt. %]
Min	0.30				0.35			Residue
Max	0.70	0.50	0.10	0.03	0.80	0.03	0.10	

movement of dislocations on the slip planes. After the rolling process, this alloy undergoes a solution heat treatment and quenching to room temperature to bring the alloying elements into a supersaturated solid solution (SSSS). This condition is referred to as temper T4. The material is soft and easy to form, but since the alloying elements are in solution, they also impede the flow of electrons and result in lower electrical conductivity [6]. Subsequently, the intermediate precipitations can then be formed through artificial aging annealing in order to set the desired strength and electrical conductivity of the material. The individual intermediate stages from the supersaturated mixed crystal to the stable phase are composed as follows [7, 8]:

$$\text{SSSS} \rightarrow \text{Cluster} \rightarrow \text{Mg, Si Co - Cluster} \rightarrow \text{GP1 - zones} \rightarrow \beta''(\text{GP2 - zones}) \rightarrow \beta' \rightarrow \beta(\text{Mg}_2\text{Si}).$$

For electric conductive applications the alloy EN AW-6101 is most common and their chemical composition is shown in Table 1 [9]. The electrical conductivity of a material is essentially controlled by two influencing variables: On the one hand, by the chemical composition and, on the other hand, the solution state of the alloying elements in the material [6]. Due to their high specific electrical resistance, the elements chromium, lithium, titanium, vanadium, and manganese reduce the conductivity of the microstructure. Manganese is of particular importance for the end use, as this is a typical by-element in a 6xxx alloy [2].

The electrical conductivity is increasing if the alloying elements are present in the structure in the precipitated state. This allows the electrons to move more freely through the material. In the solution state and with a finer distribution, the entire aluminum matrix is distorted, which is why the conductivity decreases. In contrast, the formation of precipitates reduces the strength, which is why a trade-off between these material properties must considered. The material is aged starting from temper T4 over the hardened temper T6 and finally transferred to temper T7 [9, 10].

Procedure

The product development consisted of two key aspects. First the influence of the alloying elements especially manganese on the electrical conductivity was to be identified in order to determine potential limitations for the alloy. The second step was to establish the production parameters for the solution heat treatment and the over-aging to generate the optimized mechanical and electrical properties. In Fig. 1 the time–temperature curve for the annealing process is plotted for illustration. The over-aging annealing is significantly longer than the common T6 simulation annealing within the automotive industry.

Two alloys, alloy A and alloy B, are used in the preliminary test. Alloy A has a significantly higher manganese content of 50% and slightly higher silicon and magnesium (2% each) contents compared to alloy B. Both chemical compositions comply with the specification EN AW-6101. The materials were treated to the T4 temper with the identical solution heat treatment parameters, over-aged to the T7 temper, and afterwards the achievable electrical conductivities were compared. The solution annealing dates are also identical to avoid different natural aging conditions, which cause different precipitation kinetics [11]. The samples were naturally aged at room temperature for three weeks prior to the T7 annealing step.

For the EN AW-6101 alloy, different T7 heat treatment concepts were applied in other studies:

- 7 h, 15 h, and 39 at 170 °C [12],
- 0 h to 25 h at 180 °C [13],
- 1 h to 35 h at 180 °C, 210 °C and 240 °C [14].

Based on these studies the T7 annealing was carried out using a time–temperature matrix and in total 20 variants are investigated, where four different temperatures are tested at five different holding times each. The temperature was increased in constant steps. The target corridor for achieving the mechanical and electrical properties are at least a yield strength of 150 MPa and a conductivity of 33.0 MS/m (57% IACS). After determining the advantageous chemical composition and T7 annealing, these parameters were transferred to the production process. The test material was produced in a thickness of 3.0 mm under solution heat treatment parameters of over 550 °C with a holding time of approx. 70 s. Finally, this material was characterized in terms of mechanical properties, bendability and microstructure. Hereby the new material was tested at different positions in the coil width (edge and middle) and coil length (head and tail) to ensure consistent material properties through coil annealing.

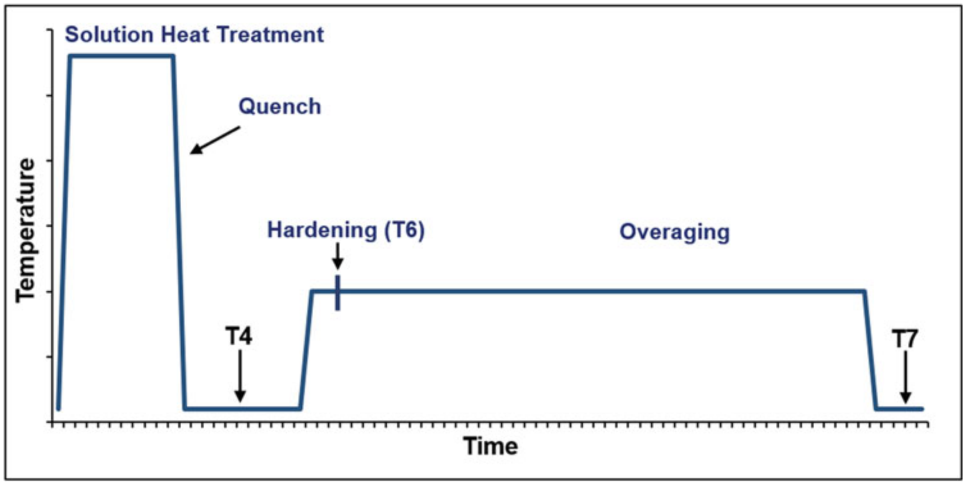


Fig. 1 Time–temperature curve for generating different material tempers for 6xxx aluminum grades

Results and Discussion

The development of the electrical conductivity for alloy A and alloy B as a function of time and temperature during over-aged annealing is shown in Fig. 2. It is confirmed, that with higher temperatures and longer annealing times, the conductivity rises as a result of the increasing precipitation processes. The difference between alloy A and alloy B is significant, with alloy B generating a consistently higher conductivity of approx. 0.4 MS/m. Further, the additional gain in electrical conductivity decreases between the individual linear temperature increasing steps. The precipitating ability of the generally low-alloyed material is thus found to be low, which is why the curves also flatten with increasing holding time. Including the long annealing times and furnace occupancy, the leverage for efficient production lies essentially in the chemical composition. The manganese content should be as low as possible and to be strictly limited. Summarized only temperatures T_3 and T_4 produce a sufficiently high conductivity of 33.0 MS/m in a reasonable time from at least the second time measuring point.

The influence of the T7 annealing on the yield strength is shown in Fig. 3 as the second important mechanical characteristic, ensuring processability of the material. The analysis only includes alloy B, which is advantageous in terms of the electrical conductivity. A clear correlation is shown: With increasing annealing time and temperature, the strength of the material decreases inversely to the increase in electrical conductivity as expected in the literature stated. The reason lies in the growing precipitation formation, whereby smaller precipitation clustering together to bigger once. Also rodlike β'-phase transforms into globular β-phase. Additionally, the grain size is growing too. All these operations ease the movement of dislocations and therefore reduce the material strength while increasing conductivity. The temperature T_4 leads to a fast softening of the material and the minimum strength of 150 MPa is already undercut at the second measuring point. The temperature T_3 shows a higher process reliability since the fourth measuring point is still above the limit. Taking process fluctuations into account, the third time measuring point at temperature T_3 provides the optimized compromise between material strength and electrical conductivity. Conversely, as the strength decreases, the elongation and the bendability of the material increase.

When implementing the test results in the production process, a third alloy composition, alloy C, was used, which again shows a reduction in the manganese content of 50% compared to alloy B. In addition, the solution heat treatment process for temper T4 was slightly modified. The main goal of T7 annealing is the precipitation process of the alloy elements. For this reason, an intensive upstream solution heat treatment is counterproductive, whereby the alloying elements are dissolved. The annealing time and temperature are therefore reduced, but at the same time must be intense enough, to allow the rolled structure to recrystallize and generate good workability. The over-aging process is controlled via thermocouples so that the metal temperature can be controlled according to the preliminary lab scale tests.

The material manufactured on a production scale achieves an electrical conductivity of 33.7 MS/m (58.1% IACS) and a yield strength of 155 MPa. This result represents a very good compromise and is very well within the desired target window for this development. The microstructure picture in Fig. 4 shows a globular grain structure. The image was obtained after an 80 s Barker etch at a magnification of 100× in the T/2 position. Within Fig. 4 the large number of fine black dots clearly shows the formed Mg_2Si-precipitations. An average grain size of approx. 50 µm is determined, which is slightly higher than in the standard production with the delivery condition T4. With a reduction in the number of grain boundaries due to grain

Fig. 2 Development of electrical conductivity as a function of temperature, time, and alloy during over-aging T7 annealing

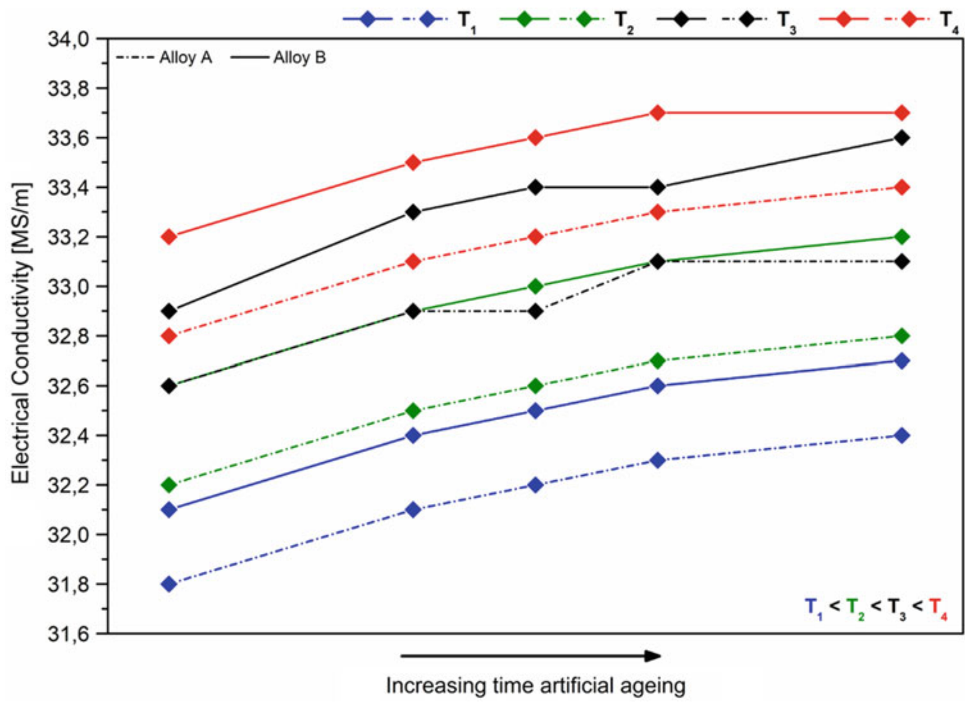
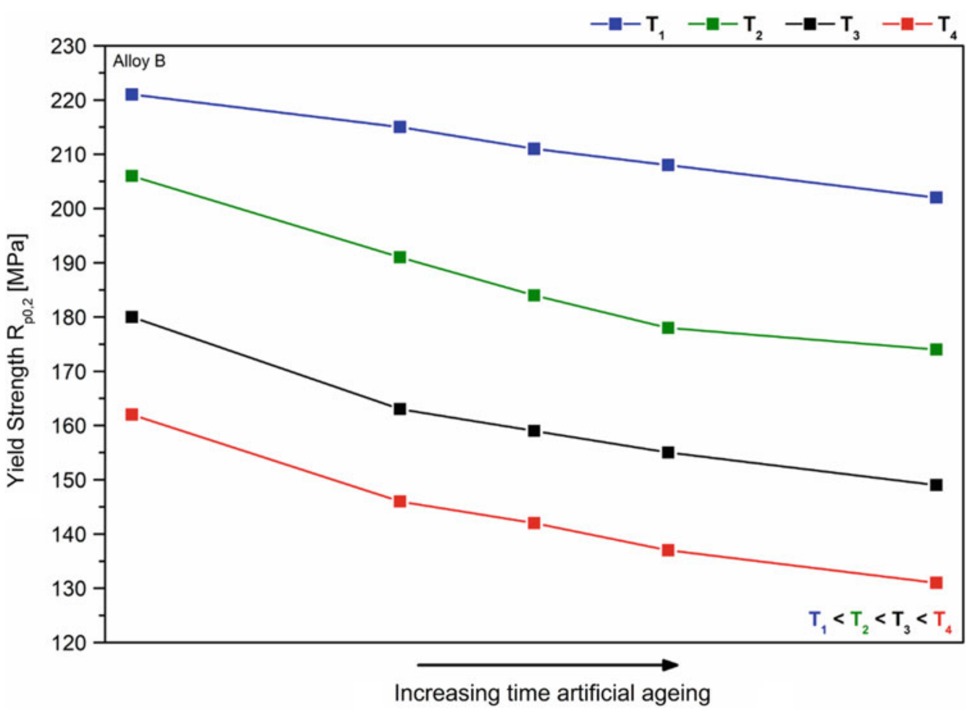


Fig. 3 Influence of T7 annealing as a function of time and temperature on the yield strength of alloy B



growth, the electrical conductivity improves, but the bending performance of the material decreases.

Finally, the last material characterization of the new product takes place by evaluating the bendability. The material is tested according to ASTM E290, where the bending radius N = 1 corresponds to the sheet thickness of 3.0 mm. A bending angle of 90° is demanded as a standard requirement for typical applications. In order to test the material to the maximum, Fig. 5 shows a 180° bend at different coil positions. The bending is carried out transversely to the rolling direction. The alloy achieves a very good bending result and shows no cracks or crack initiation lines.

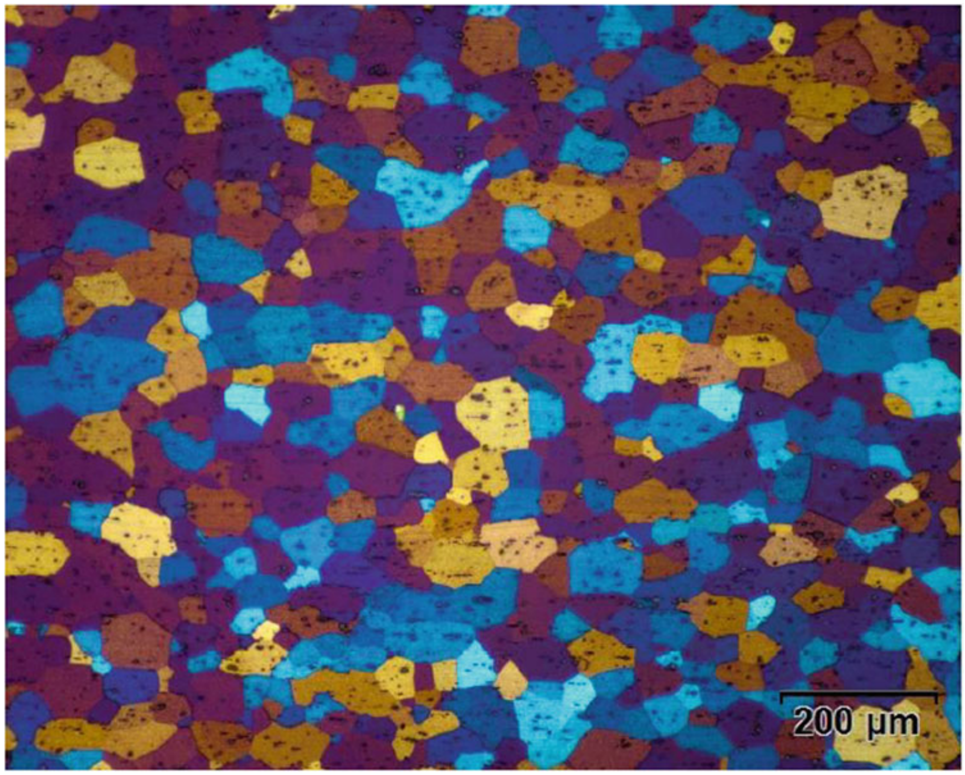


Fig. 4 Microstructure alloy C of position L-ST at T/2 with a magnification of 100:1 after 80 s Barker etching in temper T7

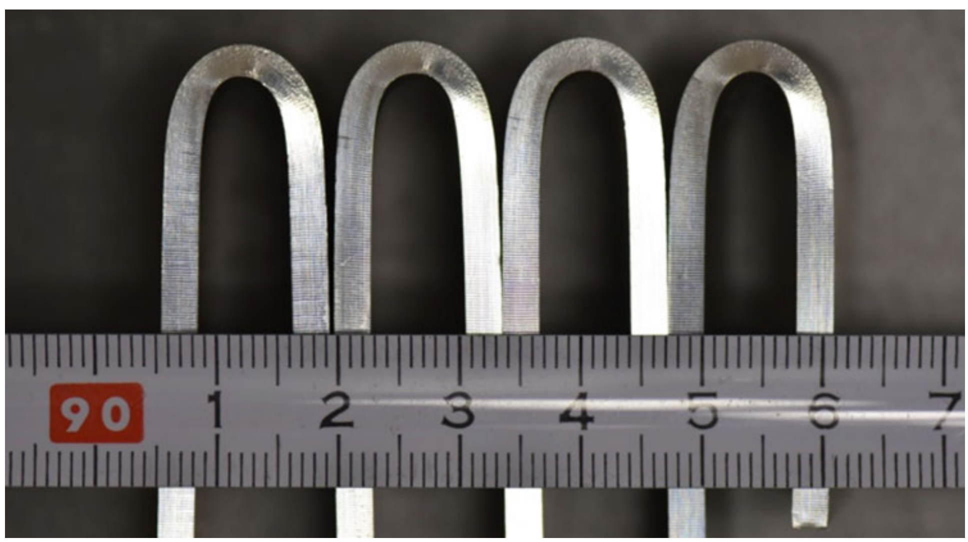


Fig. 5 Bending samples of 180° according to ASTM290 (radius N = 1) at different coil positions of alloy C transverse to the rolling direction

Conclusion

The low specific density, significantly lower price with good corrosion properties, and at the same time a very good workability including a sufficiently high electrical conductivity make 6xxx Al–Mg–Si alloys a real challenger for copper in electrically conductive applications. On the one hand, these applications can be used within the battery as bus bars in the vehicle, but also in stationary areas such as home storage systems and charging points.

The chemical composition and the over-aging heat treatment are decisive for generating the necessary mechanical properties. The proportion of the element manganese should be as low as possible. During the over-aging T7 annealing clusters and precipitation are formed, grown, and finally transformed to the Mg_2Si phase. This effect and the additional growing of the grain size increasing the electric conductivity while reducing the strength. Within the over-aging heat treatment, the temperature and time should not be too high in order not to reduce the strength of the material too much to keep a good processability.

In summary, the new 6xxx Al–Mg–Si alloy achieves the following material properties:

- Electrical conductivity up to 58.1%IACS (33.7 MS/m),
- Minimum yield strength of 150 MPa,
- Globular grain size of 50 µm,
- Bendability of 180° according to ASTM290 (radius N = 1).

This allows AMAG rolling GmbH to offer a suitable material solution for electric applications such as bus bars in electric cars.

References

1. Man Y (2016) Aluminium cables in automotive applications: Prestudy of aluminium cable uses in Scania products & failure analysis and evaluation. KTH Royal Institute of Technology, Stockholm http://kth.diva-portal.org/smash/get/diva2%3A954680/FULLTEXT01.pdf. Accessed 18 August 2023
2. Mondolfo LF (1979) Aluminum alloys - Structure and properties. Butterworths, London
3. London Metal Exchange (2023). In: LME Historical Market Data - LME Monthly Average Prices. https://www.lme.com/en/Market-data/Accessing-market-data/Historical-data. Accessed 28 August 2023
4. Flores EU, Seidman DN, Dunand DC & Vo NQ (2018) Development of high-strength and high-electrical-conductivity aluminum alloys for power transmission conductors. Light Metals 247(15):247–251. https://doi.org/10.1007/978-3-319-72284-9_34
5. Sampaio R, Zwicker MFR, Pragana JPM, Bragança I, et al. (2022). Busbars for e-mobility: State-of-the-Art Review and a New Joining by Forming Technology. In Davim JP (Ed.), Mechanical and Industrial Engineering. Materials Forming, Machining and Tribology. Springer, Cham, p 111–141. https://doi.org/10.1007/978-3-030-90487-6_4
6. Fortin PE (1972) Factors influencing electrical conductivity and strength of aluminum and its alloys. Canadian Metallurgical Quarterly 11(2):309–315. https://doi.org/10.1179/cmq.1972.11.2.309
7. Banhart J, Sin Ting Chang C, Liang Z, et al. (2010): Natural Aging in Al–Mg–Si Alloys - A process of unexpected complexity. Advanced Engineering Materials 12(7):559–571. https://doi.org/10.1002/adem.201000041
8. Aruga Y, Kozuka M, Takaki Y & Sato T (2016) Effects of natural aging after pre-aging on clustering and bake-hardening behavior in an Al–Mg–Si alloy. Scripta Materialia 116:82–86. https://doi.org/10.1016/j.scriptamat.2016.01.019
9. Khangholi S, Javidani M, Maltais A & Chen G (2022) Review on recent progress in Al–Mg–Si 6xxx conductor alloys. Journal of Materials Research 37(3):670–691.https://doi.org/10.1557/s43578-022-00488-3
10. Sauvage X, Bobruk EV, Murashkin MY, et al. (2015) Optimization of electrical conductivity and strength combination by structure design at the nanoscale in Al–Mg–Si alloys. Acta Materialia 98:355–366. https://doi.org/10.1016/j.actamat.2015.07.039
11. Pogatscher S, Antrekowitsch H, Leitner H, et al. (2011) Mechanisms controlling the artificial aging of Al–Mg–Si Alloys. Acta Materialia 59 (9):3352–3363. https://doi.org/10.1016/j.actamat.2011.02.010
12. Sunde JK, Marioara CD, Wenner S & Holmestad R (2021) On the microstructural origins of improvements in conductivity by heavy deformation and ageing of Al-Mg-Si alloy 6101. Materials Characterization 176. https://doi.org/10.1016/j.matchar.2021.111073
13. Xu X, Yang Z, Ye Y, et al. (2016) Effects of various Mg/Si ratios on microstructure and performance property of Al-Mg-Si alloy cables. Materials Characterization 119:114–119. https://doi.org/10.1016/j.matchar.2016.07.011
14. Liu CH, Chen J, Lai YX, et al. (2015) Enhancing electrical conductivity and strength in Al alloys by modification of conventional thermo-mechanical process. Materials & Design 87:1–5. https://doi.org/10.1016/j.matdes.2015.07.133