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The Influence of the Manufacturing Process on the Average Grain Size Behaviour of the 6063-Aluminum Core Alloy Clad With 4004 Alloy, O Temper

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Abstract

This paper aimed to evaluate the influence of manufacturing process of AA6063 core cladded with AA4004 on average grain size behaviour. Therefore, multiple experimental trials were conducted to investigate the effects of the homogenization soaking time of the AA6063 slabs and the final annealing soaking time on the grain size of the obtained clad coils. A correlation between the average grain size and these variables of the production process was established, indicating that specific material properties can be achieved by manipulating certain process parameters during the manufacturing process of the AA6063 core cladded with AA4004, O temper.

Keywords

AA6063 core, AA4004 clad, soaking time, average grain size

1. Introduction

By combining of AA6063 cladded with AA4004 on one side, in the O temper, a material with the extrudability and corrosion resistance of AA6063, the brazing capabilities of the AA4004 on one side, and the softness and formability of the O temper condition is obtained. This configuration can be advantageous for applications requiring both good mechanical properties and the ability to join or braze the material effectively.

Generally, the heat exchangers components are fabricated using braze-clad materials, with AA3003 as the core alloy and AA4xxx-series alloy employed as the cladding [1].

The mechanical characteristics of heat treatable AA6xxx-series alloys surpass those of AA3xxx-series alloys, providing desirable strength from the perspective of radiator manufacturers. Minimizing gauges in high-strength radiators becomes a priority to save on weight and material expenses. Utilizing these high-strength radiators enables higher internal pressure tolerance in the cooling medium, resulting in enhanced cooling efficiency and improved resistance to fatigue failure.

When comparing AA6xxx-series alloys with AA3xxx-series alloys, the heat-treated AA6xxx-series alloys exhibit significantly higher yield strength. However, AA6xxx-series alloys have certain drawbacks, including a lower melting temperature and increased susceptibility to silicon penetration from the cladding into the core. This silicon diffusion primarily occurs along grain boundaries, leading to concerns about potential adverse effects on corrosion resistance and strength. Consequently, the shape and size of the grains play a crucial role in mitigating these effects [2].

In this work the effects of the homogenization soaking time of the AA6063 slabs and the final annealing soaking time on the grain size of the obtained clad coils was investigated.

For Direct Chill (DC) cast aluminum alloy slabs, it is generally better to have a relatively thin shell zone rather than a thick one. The shell zone refers to the outer solidified layer that forms during the casting process before the entire slab solidifies. The primary reason for aiming for a thinner shell zone is to achieve better casting quality and mechanical properties in the final product [3].

The homogenization treatment has a significant influence on the shell area of DC cast aluminum alloy slabs. The primary purpose of the homogenization treatment is to improve the microstructure and eliminate or reduce segregation and inhomogeneity in the cast material, including the shell area [4].

During the casting process, certain alloying elements may segregate towards the boundaries of the grains, leading to compositional variations within the shell area. The homogenization treatment involves heating the cast slab to a specific temperature for a certain duration, allowing the alloying elements to diffuse and distribute more evenly. This process reduces segregation and promotes uniformity in the shell area [5].

The shell area is particularly prone to defects like porosity and inclusions due to rapid solidification during casting. The homogenization treatment helps in dissolving and redistributing gas and impurities trapped in the shell region, thereby reducing defects and improving the overall quality of the casting [6].

Overall, the homogenization treatment plays a crucial role in improving the quality, mechanical properties, and uniformity of the shell area in Direct Chill cast aluminum alloy slabs. It enhances the casting's overall integrity and helps achieve a more uniform microstructure, making the slab more suitable for subsequent processing and desired end-use applications.

In the same time, the final annealing treatment duration can significantly influence the grain size of aluminum alloy clad coils. Annealing is a heat treatment process used to enhance the material properties, including grain size control, which is a critical factor that impacts the mechanical and physical properties [7].

The results obtained from the study enable us to establish correlations between the technological process variables and the average grain size of the AA6063 core cladded with AA4004, O temper.

2. Experimental

The experiments were conducted on AA6063 core cladded with AA4004, O temper, 4 mm thickness. The slabs were obtained by Direct-Chill (DC) casting, furthermore the AA6063 slabs were homogenized using two different soaking time: 10 h vs 16 h. These AA6063 slabs were then divided into two groups of 4 slabs based on their homogenization soaking time.

Before the cladding operation, an essential step involved stretching the AA4004 clad plates to reduce internal stress and ensure evenness. This stretching operation was carried out using the Danieli 18MN Fata Hunter stretcher (Figure 1), which was equipped with a specialized permanent elongation measurement system based on incremental position encoders.

Fig. 1. Independent equipment for the research of the residual stress removal process for the aluminium alloy plates with thickness lower than 20 mm, provided with the latest technology and commissioned in 2019 year, in the ALRO plant in Romania

Subsequently, all AA6063 slabs underwent scalping, were clad with AA4004, preheated, and hot rolled. The resulting coils from each group of slabs were then cold rolled using the same cold pass schedule.

Finally, each group of obtained products was further divided into two subgroups. For each newly formed subgroup, a different holding period (2 h vs 4 h) was applied for the homogenization treatment of the coils in order to obtain the desired O temper.

The samples for the metallographic analyses were taken after the homogenization of AA6063 slabs having the same chemical composition according to the Table 1, but with different holding time for the homogenization treatment, 10 h vs 16 h, respectively.

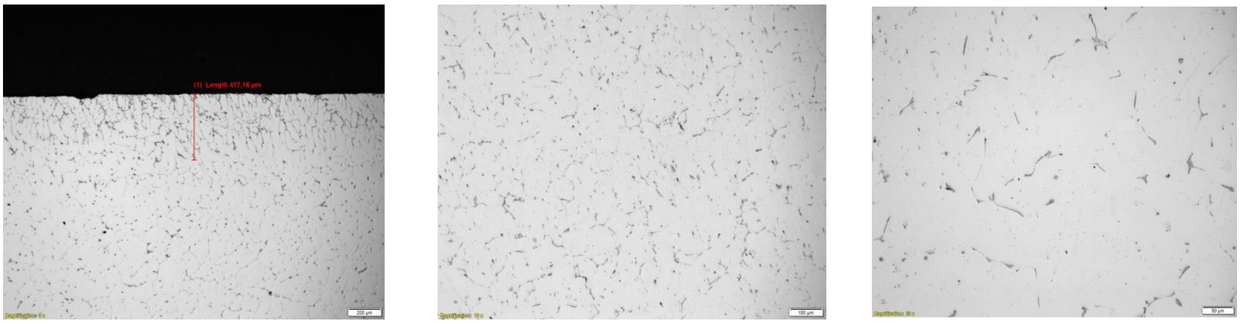
Table 1. Chemical composition of AA6063 slabs used in the experiments (mass fraction, %).

Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Other Elements		Al
								Each	Total	
0.48	0.24	0.03	0.05	0.67	0.01	0.03	0.03	≤0.05	≤0.15	98.47

To ensure effortless identification, every sample was punched and assigned a unique number.

3. Results. Discussion

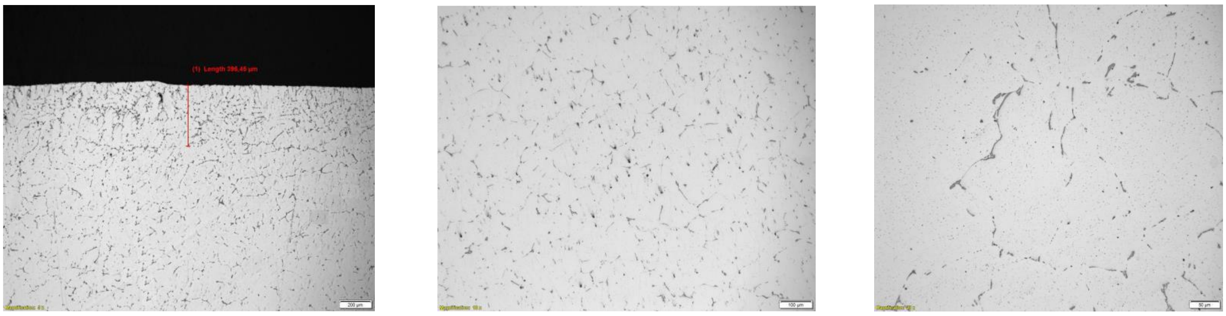
The shell zone and the phase distribution in homogenized AA6063 slabs with different soaking times, 10 h vs 16 h, respectively, are presented in Figure 2.



a. The shell zone – 417.16 μm – maximum value

b. Phase distribution – near the surface

c. Phase distribution – quarter



d. The shell zone – 396.45 μm – maximum value

e. Phase distribution – near the surface

f. Phase distribution – quarter

Fig. 2. The shell zone and the phase distribution in homogenized AA6063 slabs with different soaking times, 10 h – first row vs 16 h – second row, respectively

The microstructure analysis achieved on the slab samples highlighted a uniform distribution of the phases in the analysed sections, with areas where the phases are not segmented (Figure 2, c and f).

The minimum value of thinner shell zone (385 μm) was obtained for slabs homogenized with a long soaking time, 16 h vs 10 h, respectively. The results obtained for the remaining slabs are shown in Table 3. For AA6063 slabs that underwent homogenization with a soaking time of 10 hours, an average shell zone thickness of 390 μm was obtained, compared to 423 μm for a soaking time of 16 hours.

A thin shell zone leads to finer and more uniform grain structures in the casting. This results in improved mechanical properties, such as increased strength and ductility, making the final product more reliable and easier to work with.

Table 2 provides a summary of the metallographic analyses results. For each of the eight slabs from the same casting charge, the maximum shell area size, β→α transformation, and average grain size were determined.

Also, the data from Table 2 are graphically represented in the following graphs (Figures 3 – 6).

Also, the values determined for the β→α transformation were higher (Figure 4) for the samples taken from the slabs with the longer homogenization soaking time (16 h).

Table 2. The maximum shell area size, β→α transformation and average grain size for AA6063 homogenized slabs with different soaking time: 10 h vs 16 h

No.	Soaking time [h]	Maximum shell area size [μm]	β→α transformation in middle area [%]	Grain size for AA6063 slabs			
				Average grain size [μm]		Class according ASTM E112	
				Quarter	Middle	Quarter	Middle
1	**10 h**	417.16	88.9	151.08	171.8	2.5	2
2		422.94	88.23	154.36	173.91	2.5	2
3		427.25	88.41	157.06	174.42	2.5	2
4		426.46	88.62	159.71	174.85	2.5	2
5	**16 h**	391.42	89.29	148.63	163.68	2.5	2.5
6		385.62	89.34	146.16	159.84	2.5	2.5
7		396.45	89.33	144.92	157.07	2.5	2.5
8		384.71	89.31	149.27	155.66	2.5	2.5

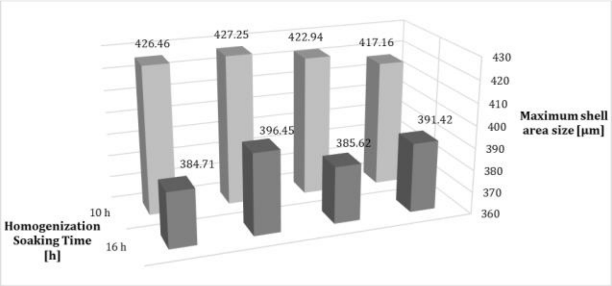


Fig. 3. Maximum shell area size depending on the homogenization soaking time

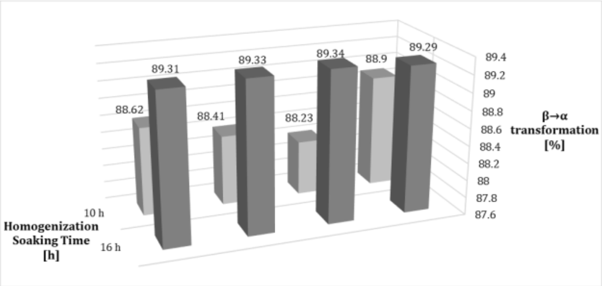


Fig. 4. β→α transformation in middle area depending on the homogenization soaking time

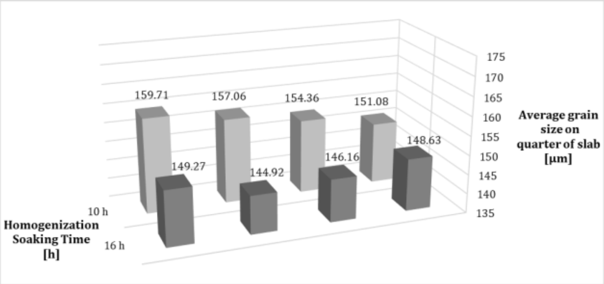


Fig. 5. Average grain size on quarter of AA6063 slab depending on the homogenization soaking time

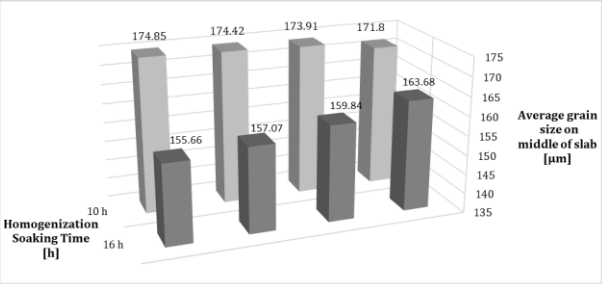
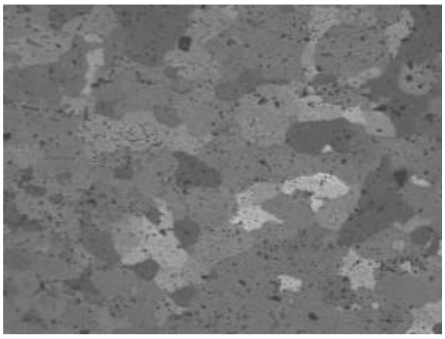


Fig. 6. Average grain size on middle of AA6063 slab depending on the homogenization soaking time

The degree of β→α transformation refers to the process of converting the β phase (metastable phase) into the α phase (stable phase) during the homogenization process. When the degree of β→α transformation is increased, homogenization allows all particles in the alloy to reach a uniform temperature, facilitating the consistent and complete transformation of the β→α phase, which leads to a uniformity of chemical composition and a reduction of concentration gradients [8].

Furthermore, the average grain size values were found to be lower for the samples taken from slabs that underwent longer homogenization times compared to those with shorter times, with class 2.5 versus class 2.0 for the samples extracted from the middle of the slab (Table 2, Figure 6).

The grain structure of the cladded material was fully recrystallised as expected for “O” temper material (Figures 7 and 8). The cladded products obtained from AA6063 slabs with longer homogenization soaking time (16 h) and a shorter time for annealing soaking time (2 h) recorded lower values for the grain size (class 5.5 vs 5.0) compared to the cladded products for which the core slab was homogenized with a shorter time (10 h) and for which the annealing was done with a longer time (4 h). All the obtained results are displayed graphically in the Figure 9.



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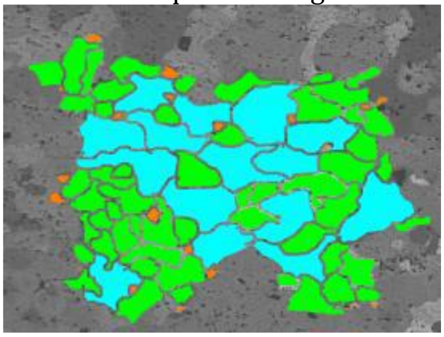

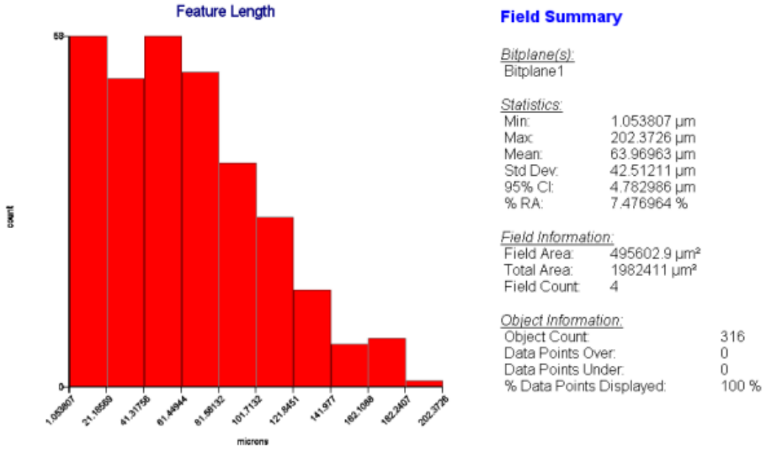

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% RA:       7.476964 %

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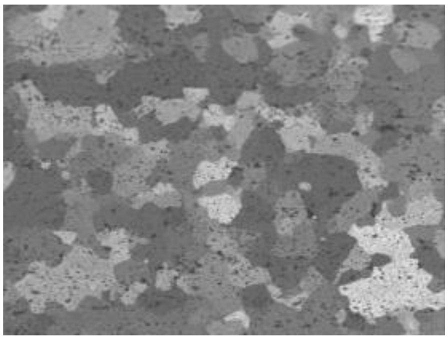
b. Detected image c. Image Analysis Measurements

Fig. 7. The grain structure (a, b) and the histogram (c) of the grain size for the 6063-aluminum core alloy clad with 4004 alloy, O temper, 4 mm thickness obtained from AA6063 slab homogenized with 10 h soaking time and 4 h for the annealing time of the clad product



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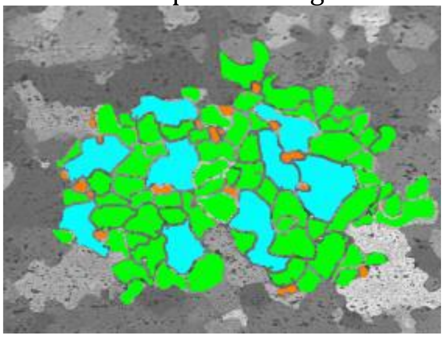

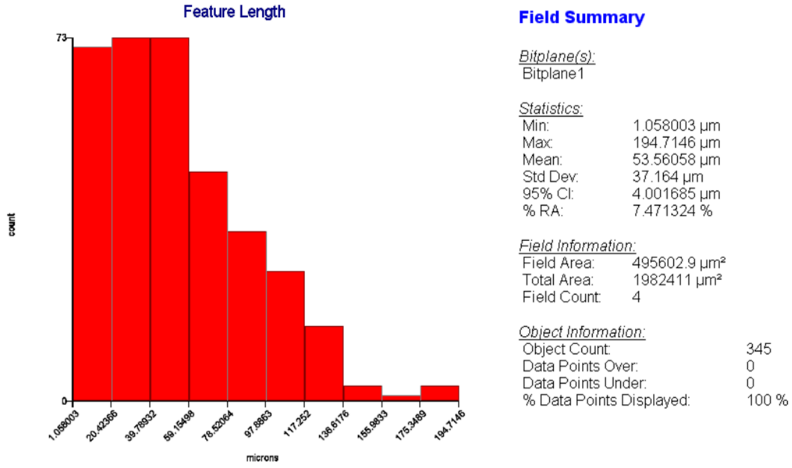

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b. Detected image c. Image Analysis Measurements

Fig. 8. The grain structure (a, b) and the histogram (c) of the grain size for the 6063-aluminum core alloy clad with 4004 alloy, O temper, 4 mm thickness obtained from AA6063 slab homogenized with 16 h soaking time and 2 h for the annealing time of the clad product

The smallest grain sizes were achieved for the slabs that underwent longer homogenization soaking times (16 h), but the resulting clad products were annealed with shorter soaking times (2 h).

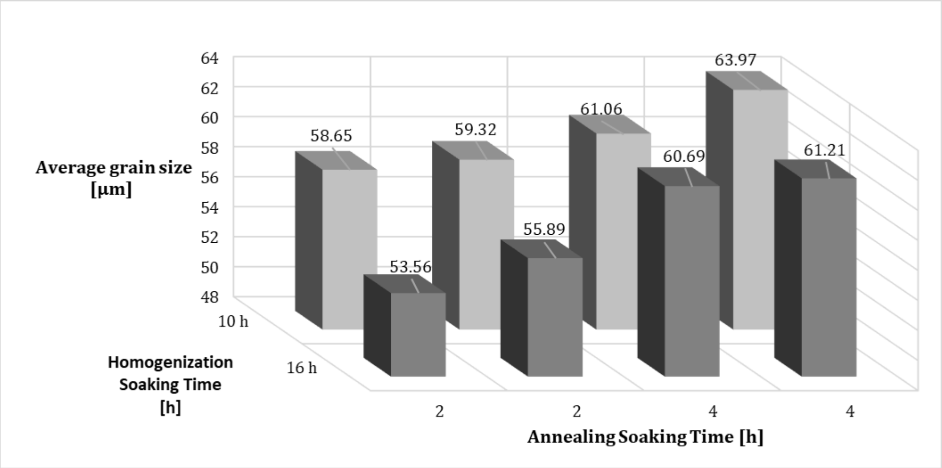

Fig. 9. The influence of the homogenization soaking time of AA6063 slabs and of the annealing soaking time of the clad products with AA4004 on the average grain size behaviour of the 6063-aluminum core alloy clad with 4004 alloy, O temper

Instead, the highest values for grain size were recorded for the annealing treatment at 4 h, while the influence of the homogenization treatment on the slabs had a minimal effect on the obtained results.

5. Conclusions

Homogenization is a critical step in processing aluminum alloys as it enhances the β→α transformation, equalizes the chemical composition, and minimizes concentration gradients. It allows for recrystallization and grain growth control in the shell area.

For AA6063 slabs subjected to homogenization with a soaking time of 10 h, the resulting average shell zone thickness was calculated at 390 µm, while those homogenized with a soaking time of 16 hours exhibited a slightly higher average shell zone thickness of 423 µm.

Homogenization encourages the formation of a fine and homogeneous grain structure, leading to improved mechanical properties and reduced anisotropy in the slab.

Furthermore, the values obtained for the β→α transformation were found to be higher in the samples extracted from the slabs subjected to a longer homogenization soaking time (16 h vs 10 h).

Moreover, the duration of annealing directly affects the extent of grain growth. Longer annealing times allow more time for grain boundary mobility, leading to increased grain growth. This is because the extended duration allows more atoms to diffuse across grain boundaries, promoting the growth of existing grains.

The cladded products produced from AA6063 slabs with a longer homogenization soaking time (16 h) and a shorter annealing soaking time (2 h) exhibited smaller grain sizes (class 5.5) compared to the cladded products obtained from slabs with a shorter homogenization time (10 h) and a longer annealing time (4 h), which had larger grain sizes (class 5.0).

The duration of annealing must be carefully controlled to achieve a homogeneous grain size distribution throughout the clad coils.

Longer annealing times require more energy and time, which can increase production costs. Balancing the desired grain size with economic considerations is essential in the industrial manufacturing of aluminum alloy clad coils.

In summary, the duration of the final annealing soaking time is a critical parameter for controlling the grain size of aluminum alloy clad coils. The optimal annealing soaking time must be determined based on the specific requirements of the application and the desired material properties. By adjusting particular process parameters during the manufacturing of AA6063 core cladded with AA4004, O temper, it becomes possible to attain specific material properties.

Additional research is needed to conduct specific analyses, including evaluations of mechanical properties and behaviour after brazing. These investigations are essential as they have the potential to influence the outcomes of the experiments mentioned in this study.

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