Heat treatment of the EN AC-42100 alloy within industrial furnaces: the effect of treatment parameters on mechanical properties

M. Merlin, E. Baroni, A. Fortini, C. Soffritti, F. Feggi

Within the aluminum foundry, the EN AC-42100 alloy is the most extensively employed for high-pressure or low-pressure casting processes due to its remarkable balance between castability and final properties of the castings. The mechanical properties of components intended for structural applications can be enhanced both by specific treatments applied to the melt and through heat treatments on the castings. The goal is to ensure an optimal combination of mechanical properties to meet the defined technical specifications for the end user. Hence, setting the proper heat treatment cycle for new components can be challenging and typically involves an iterative procedure to ascertain the optimal process parameters. Moreover, each furnace exhibits its own technical and operating characteristics resulting in variable outcomes when employing identical treatments across furnaces from different manufacturers.

This paper presents the results of an experimental study performed in collaboration with the company HTT – Heat Treatment Torri to investigate the correlation between heat treatment parameters and the mechanical properties of experimental gravity castings treated in industrial furnaces. Specifically, in the first phase, the effect of different solution times was examined to identify the optimal solution time through tensile and hardness tests while keeping the aging parameters constant. Based on the results of such experiments, the second phase comprised a constant solution treatment and the analysis of combinations of aging times and temperatures to maximize both performance and productivity by the specified technical requirements defined by the customer.

KEYWORDS: EN AC-42100 ALUMINUM ALLOY, HEAT TREATMENT, MECHANICAL PROPERTIES, MICROSTRUCTURE

INTRODUCTION

Aluminum alloys have long played a crucial role in several engineering fields owing to their peculiar features, including specific mechanical strength, high thermal and electrical conductivity, good formability, and recycling properties [1]. The Al-Si alloys, in particular, are widely used in foundry processes due to their remarkable castability, reduced susceptibility to hot cracking, and the effective role of silicon in minimizing solidification shrinkage. Among these alloys, the hypoeutectic AlSi7Mg0.3 alloy is of great interest for foundry applications [2, 3]. It exhibits excellent mechanical and technological properties, crucial in the automotive sector, e.g. for the production of frames and suspensions through sand casting, shell casting, or low-pressure die casting (LPDC) techniques. To optimize the mechanical properties of castings

M. Merlin, D. Gramigna, E. Baroni, A. Fortini
University of Ferrara

F. Feggi
HTT Heat Treatment Torri Srl

produced with this alloy is essential to conduct a thermal treatment sequence that involves solution heat treatment followed by artificial aging, known as the T6 heat treatment [4]. The initial phase of the treatment consists of a high-temperature solution stage, followed by rapid quenching in water, properly added with specific kinds of polymers, and thermostated between 60 °C and 70 °C. In the subsequent aging phase, the components are reheated to a predetermined temperature, significantly lower than the solution temperature, to achieve the formation of fine and dispersed intermetallic reinforcing phases. The aim of the solubilization treatment is to dissolve the majority of coarse intermetallic phases, particularly those containing Mg, which are formed during the early solidification stage [4]. This can be reached by maintaining the material above 500 °C for 4 to 8 hours [2]. Furthermore, both the duration and temperature of the solution treatment have been proven to directly influence the morphology of the eutectic Si in Al-Si alloys and, consequently, the final mechanical properties of the castings [5]. The quenching process, which occurs at the end of the solution stage, aims to cool the material as rapidly as possible to a temperature close to ambient temperature, to obtain an oversaturated solid solution [6-7]. The third and final phase of the T6 heat treatment is artificial aging, which involves heating the material for several hours, typically above 150 °C. Aging is intended to promote the formation of semi-coherent precipitates within the lattice of the primary α-Al phase, maximizing the mechanical properties through precipitation as the strengthening mechanism. To set up and optimize heat treatment parameters in both the solution and aging stages, necessary to gain the optimal compromise between the different required mechanical characteristics of castings, have been a matter of great scientific and industrial interest for many years. The solution temperature should be between 500 °C and 550 °C, whereas a higher temperature leads to better mechanical properties, but increases the risk of melting low-melting compounds at grain boundaries, thus compromising the material integrity. Furthermore, it is known that in the aging phase, time and temperature are interdependent in determining the optimal condition for matrix hardening: as the temperature increases, it has been observed that the peak of mechanical properties (yield and ultimate strength) can be achieved with shorter holding times, but it is also true that when the same temperature increases, the peak becomes progressively smaller [8]. It should be highlighted that the above-reported findings and correlations result from experiments conducted in scaled-down furnaces, namely laboratory-scale furnaces, which neglect the scale effect of industrial furnaces and the influence of the thermal mass of sample baskets and potential heat losses.

The present study, performed in collaboration with the company HTT - Heat Treatment Torri, aims to optimize the process parameters in the different stages of the T6 heat treatment in industrial-type furnaces. The research was carried out in two phases. Firstly, the influence of different solution times at a fixed temperature on the mechanical properties of an EN AC-42100 aluminum alloy was investigated, considering specific quenching and aging treatments. Once the ideal solution condition was determined, the second phase was focused on identifying the optimal parameters for the artificial aging treatment: different combinations of temperature and holding times were selected based on existing literature [8,9] and the expertise of the involved company. Finally, their impact on the mechanical and microstructural properties of the alloy was evaluated.

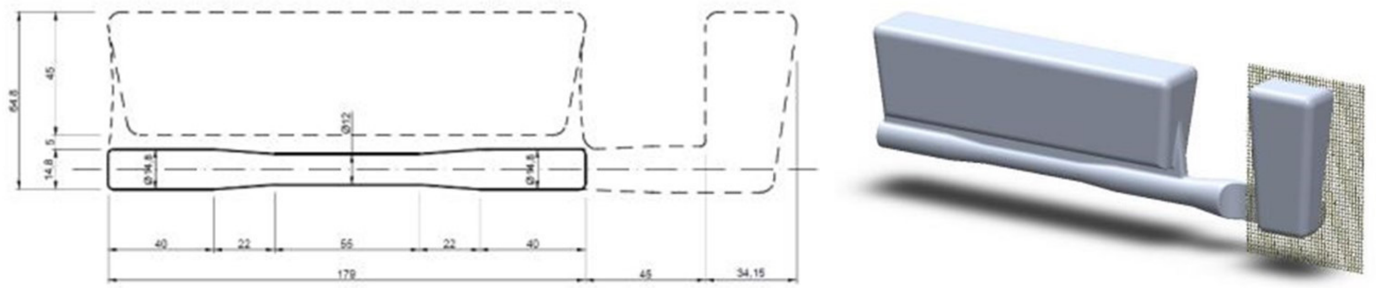
MATERIALS AND METHODS

The castings used for the study were made of EN AC-42100 aluminum alloy by Fonderia S. Possidonio Srl (Modena, Italy) using a steel mold. The alloy was subjected to liquid treatments that involved the addition of Al5TiB1 grain refiners and Al-10%Sr master alloy rods. To ensure the compositional homogeneity, all samples were cast from the same ladle. The chemical composition of the alloy was determined using Optical Emission Spectroscopy (OES) technique. Table 1 presents the average and relative standard deviation of six measurements, as well as the reference chemical composition for the EN AC-42100 alloy according to UNI EN 1706 standard. The results highlight the correspondence between the investigated alloy and the specifications outlined by the standard. The Ti and Sr contents indicate the efficacy of refinement and modification treatments, respectively

Tab.1 - Chemical composition (wt. %) of the investigated EN AC-42100 alloy.

	Si	Fe	Cu	Mn	Mg	Cr	Ni	Zn	Pb	Sn	Ti	Sr	others	Al.
Average	6.690	0.105	0.001	0.003	0.365	0.0026	0.005	0.003	0.002	0.0005	0.117	0.026	0.0093	92.676
Std. Dev.	0.077	0.009	0.000	0.000	0.018	0.0002	0.000	0.001	0.000	0.0002	0.006	0.001	0.0011	0.062
UNI EN 1706	6.5 - 7.5	0.19	0.05	0.1	0.25 – 0.45	-	-	0.07	-	-	0.25	-	-	Rim.

The alloy was cast into a specific mold, as reported in Fig. 1, to obtain samples for the heat treatment investigation. From each of the castings a tensile test specimen was machined to test the mechanical behavior resulting from the heat treatment route.



(a) (b)

Fig.1 - Getti in lega EN AC-42100 colati per l'attività di ricerca: a) rappresentazione 2D e b) 3D.

The heat treatments, carried out by the company HTT - Heat Treatment Torri, were performed in various types of industrial furnaces with different configurations. For the solution treatment, a semi-continuous tunnel furnace consisting of four chambers, with the first chamber designated for pre-treatment and the last chamber used for quenching the sample basket in water at a temperature of 70 °C, was employed. Pneumatic movement between chambers was possible only when the entire furnace reached the set temperature and after the designated holding time. For the aging treatments, a batch-type furnace was employed and the temperature uniformity was checked inside the furnaces using thermocouples and a data acquisition and control system. The parameters for the heat treatments were selected based on the company's experience and literature studies that utilized laboratory-scale furnaces. The experimental activity was divided into two steps, following the experimental plan summarized in Table 2.

Tab.2 - Heat treatments sequence and parameters.

	Solution		Aging	
	Temperature [°C]	**Time [min]**	**Temperature [°C]**	**Time [min]**
Step 1	535	120	160	300
		240		
		360		
Step 2	535	Value obtained from Step 1	135	120
				240
				360
			160	180
				240
				360
			200	120
				180
				240

Step 1 was devoted to studying the influence of the solution treatment duration (120, 240 and 360 minutes) for a fixed temperature (535 °C). It followed standard aging at 160 °C for 300 minutes. Step 2 investigated the effect of different combinations of aging temperatures (135, 160 and 200 °C) and duration (120, 240 and 360 minutes) on samples previously solution treated according to the optimized parameters obtained from Step 1. For each condition, n° 5 castings were analyzed to ensure the statistical significance of the data, resulting in a total of n° 60 castings. To ensure tests that resembled real-world conditions, and to obtain reproducible heating and holding ramps, the baskets were also filled with scrap pieces. After solution quenching, the castings were extracted and stored at -18 °C to prevent natural aging; only once all the predetermined aging treatments were performed, tensile test specimens were machined from the castings to investigate the mechanical properties of the alloy under the different combinations of parameters. Tensile tests were conducted using a QUASAR 50 machine (Galdabini S.p.a., Cardano al Campo, Italy) with a load cell of 50 kN, in accordance with UNI EN ISO 6892-1. For the comparison of different treatment conditions, the ultimate tensile strength (UTS), yield strength (YS), and percentage elongation at fracture (Ef %) were considered. Brinell hardness tests (HBW2.5/62.5) were also conducted using an Ernst AT130D hardness tester to get the variation in mechanical properties due to the performed treatments. Moreover, after Step 1, microstructural analysis was performed on three tensile test specimens, one for each investigated solution time. Samples were observed using a Leica DMi8 A metallographic optical microscope (Leica Microsystem, Wetzlar, Germany) equipped with LAS v4.13 image acquisition software.

RESULTS AND DISCUSSION

The average values of the tensile tests carried out on specimens drawn from castings treated according to the heat treatment parameters defined for Step 1 are summarized in Table 3. It can be observed that both UTS and YS increase with increasing solution time, although no significant variations are evident among the different conditions. In this regard, Zhang et al. [9] demonstrated that mechanical properties increased as a result of diffusion phenomena that occur within the first 30 minutes of solution treatment. As for Ef %, the highest value was obtained for 240 minutes of solution at 535 °C.

Tab.3 - Tensile test results (average values and standard deviations) for the investigated solution times (Step 1).

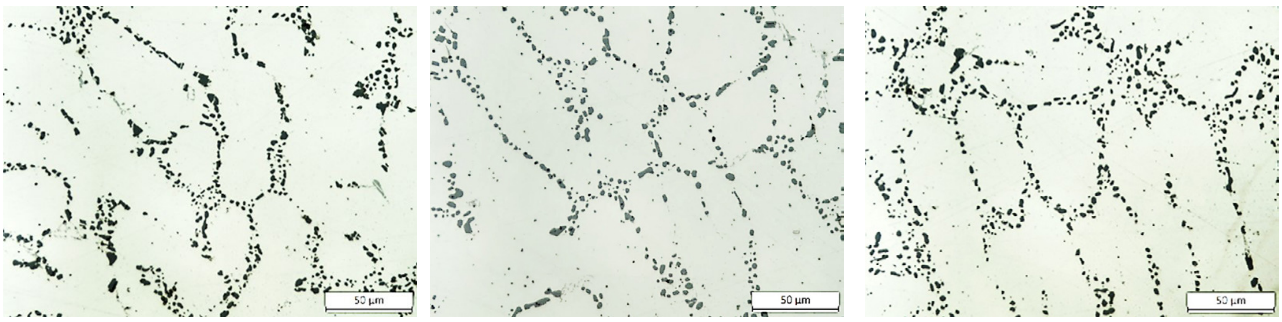
	535 °C x 120 min	535 °C x 240 min	535 °C x 360 min
UTS [MPa]	291.2 ± 13.8	309.1 ± 3.9	315.0 ± 2.7
YS [MPa]	222.2 ± 5.4	231.3 ± 6.3	241.9 ± 1.9
Ef% [#]	7.35 ± 2.55	9.90 ± 1.41	9.00 ± 1.37

Table 4 shows the Brinell hardness test results obtained for the investigated solution times of Step 1. As seen, and considering the standard deviations, hardness did not vary significantly with increasing solution time, despite showing a slightly increasing trend as tensile properties.

Tab.4 - Brinell hardness test results (HBW2.5/62.5) for the investigated solution times (Step 1).

	535 °C x 120 min	535 °C x 240 min	535 °C x 360 min
HBW2.5/62.5	94.6 ± 3.4	95.8 ± 2.9	98.8 ± 2.6

Following the tensile tests, a microstructural examination was conducted. Figure 2 displays the representative optical micrographs of the different solution conditions.The microstructure consists of α-Al dendrites and a eutectic structure; the Si phase appears correctly modified. A low amount of Fe-based intermetallic phases was detected.



(a) (b) (c)

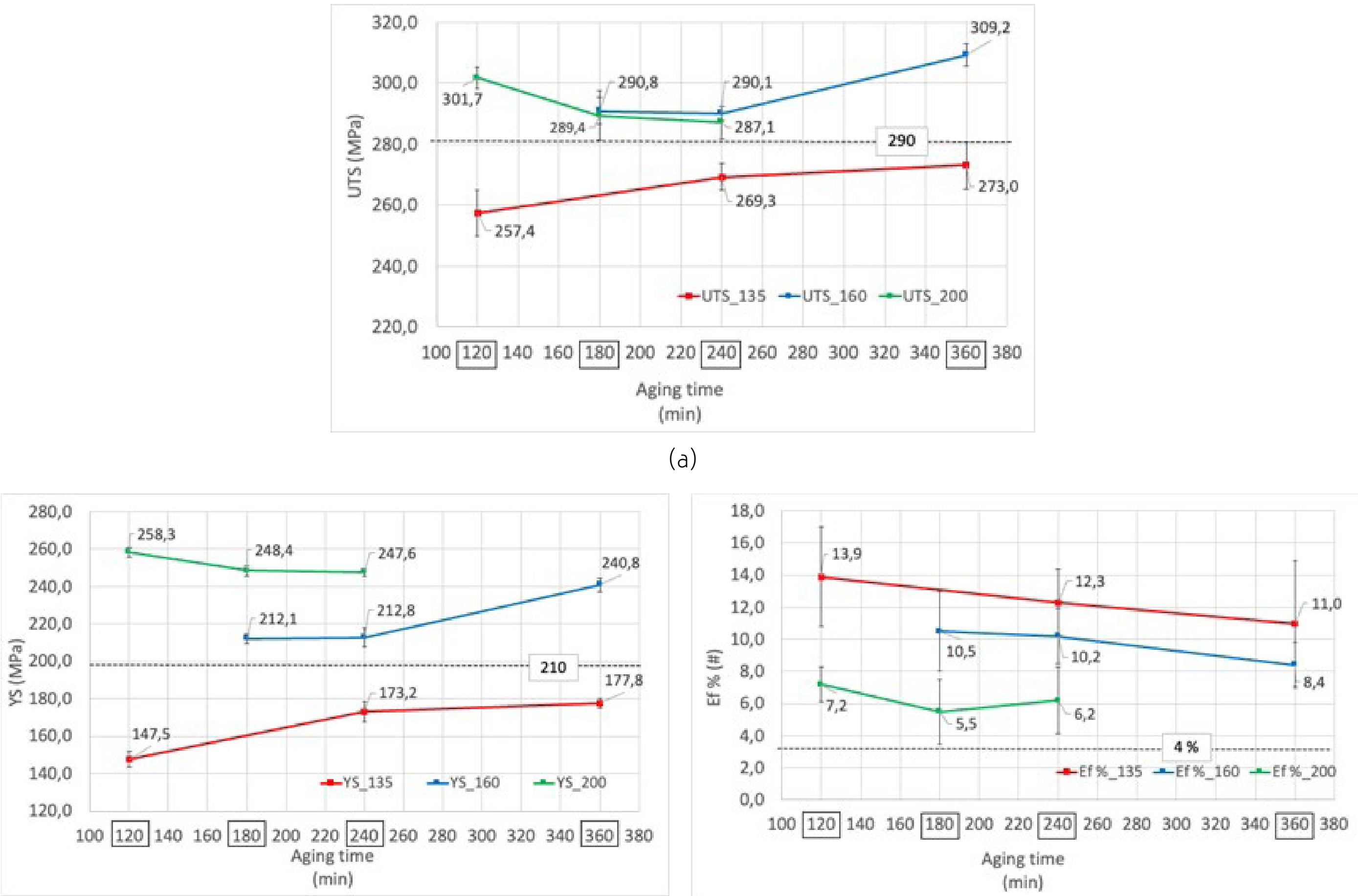
Fig.2 - Optical micrographs of the investigated solution treatment at 535 °C: a) 120 min, b) 240 min and c) 360 min.

Based on the results from the mechanical and microstructural characterization of Step 1, the solution treatment at 535 °C for 240 minutes provided the best mechanical properties. Considering that this solution treatment guarantees a favorable performance-to-cost ratio for the company compared to other longer treatment times, it was adopted as the solution treatment for subsequent investigations. Hence, Step 2 focused on investigating the influence of different combinations of aging times and temperatures while keeping the solution treatment parameters constant (535 °C for 240 minutes). Table 5 presents the average values and corresponding standard deviations of UTS, YS, and Ef % for the investigated aging parameters.

Tab.5 - Tensile test results for the investigated aging temperatures and times (Step 2).

	135 °C x 120 min	135 °C x 240 min	135 °C x 360 min
UTS [MPa]	257.4 ± 7.5	269.3 ± 4.3	273.0 ± 7.8
YS [MPa]	147.5 ± 4.2	173.2 ± 5.4	177.8 ± 7.8
Ef % [#]	13.9 ± 3.1	12.3 ± 2.1	11.0 ± 3.9
	160 °C x 180 min	**160 °C x 240 min**	**160 °C x 360 min**
UTS [MPa]	290.8 ± 4.4	290.1 ± 2.4	309.2 ± 3.6
YS [MPa]	212.1 ± 2.6	212.8 ± 5.2	240.8 ± 3.8
Ef % [#]	10.5 ± 2.5	10.2 ± 1.7	8.4 ± 1.4
	200 °C x 120 min	**200 °C x 180 min**	**200 °C x 240 min**
UTS [MPa]	301.7 ± 3.5	289.4 ± 8.0	287.1 ± 5.3
YS [MPa]	258.3 ± 2.7	248.4 ± 2.9	247.6 ± 1.9
Ef % [#]	7.2 ± 1.1	5.5 ± 2.0	6.2 ± 2.1

Figure 3 summarizes the tensile test results of Step 2: it can be seen that at lower temperatures (135 °C and 160 °C), the best mechanical properties (UTS and YS) are reached for longer aging times; nevertheless, for aging performed at 135 °C, the minimum targeted values of 290 MPa for UTS and 210 MPa for YS are not reached. In contrast, for the highest aging temperature (200 °C), the best mechanical properties were achieved with shorter aging durations (120 minutes). This trend is supported by existing literature studies [8]. For all the performed treatments, the 4 % threshold value for Ef % was overcome.



(a)

(b) (c)

Fig.3 - Tensile test results for different aging conditions (Step 2): a) UTS, b) YS and c) Ef %.

Table 6 summarizes the Brinell hardness test results for the investigated aging conditions of Step 2. The same values are also displayed in Fig. 4: the highest values correspond to the 200 °C for 120 minutes and 160°C for 360 minutes conditions. Considering the standard deviations of the results, only the latter condition and all the aging performed at 200 °C are able to overcome the threshold value of 90 HBW2.5/62.5.

Tab.6 - Brinell hardness test results (HBW2.5/62.5) for the investigated aging conditions (Step 2).

	135 °C x 120 min	**135 °C x 240 min**	**135 °C x 360 min**
HBW2,5/62,5	77.2 ± 0.9	81.8 ± 1.4	84.8 ± 1.0
	160 °C x 180 min	**160 °C x 240 min**	**160 °C x 360 min**
HBW2,5/62,5	89.9 ± 2.3	90.5 ± 1.5	97.6 ± 0.8
	200 °C x 120 min	**200 °C x 180 min**	**200 °C x 240 min**
HBW2,5/62,5	97.1 ± 0.7	94.3 ± 1.2	94.5 ± 0.6

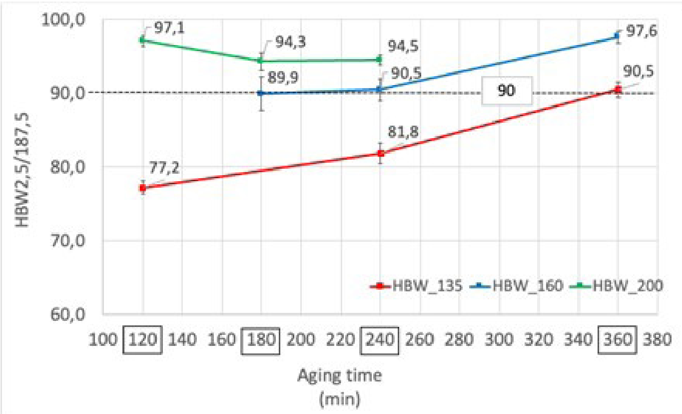


Fig.4 - Graph of the Brinell hardness test results (HBW2.5/62.5) for the investigated aging conditions (Step 2).

CONCLUSIONS

This study focused on analyzing the T6 heat treatment parameters performed in industrial furnaces to optimize the mechanical properties of the EN AC-42100 alloy. In the first step of the study, different holding times of a solution treatment performed at 535 °C were investigated to achieve the best compromise between mechanical properties and treatment times at the end of a subsequent aging treatment carried out at 160 °C for 300 minutes. In the second step, the influence of different combinations of aging times and temperatures on the mechanical properties was analyzed, while keeping as constant the solution conditions defined as optimal in the first step. Based on the experimental evidence, the following observations can be made:

• In the first step, solution duration affects the mechanical properties: UTS and YS increased with the solution time, despite the increment was not so remarkable, in particular passing from 240 minutes to 360 minutes of holding time. Ef % showed the highest value for the specimens treated with a solution time of 240 minutes, suggesting that a longer time is unnecessary and not cost-effective;

• Hardness values did not vary significantly with increasing solution duration, although there was a slight increasing trend in the average values. The standard deviations indicated relatively low variability in hardness;

• Microstructural analysis conducted in samples subjected, in the first step, to different holding times, revealed the typical microstructural features of an hypoeutectic EN AC-42100 alloy whose melt is accurately modified. A low amount of Fe-based intermetallics was detected, so confirming the significant role of the combination of both solution and aging parameters in the evolution of mechanical properties;

• As for aging, at lower temperatures (135 °C and 160 °C), the highest mechanical properties (UTS and YS) were reached for longer aging times. Nevertheless, all the aging treatments performed at 135 °C were not able to overcome the threshold values of 210 MPa and 290 MPa for YS and UTS, respectively. Considering the standard deviations of the results, among the aging treatments carried out at 160 °C only the holding time of 360 minutes was able to guarantee suitable mechanical properties. In contrast, for higher temperatures (200 °C), the highest mechanical properties were achieved with the shortest aging duration.

ACKNOWLEDGEMENTS

The authors wish to thank Eng. Davide Gramigna for his effective contribution to the experimental investigation.

REFERENCES

[1] Kaufman J. G., Introduction to aluminum alloys and tempers, ASM International, Materials Park, 2000, p. 87.
[2] Stroh J., Sediako D., Hanes T., Anderson K., Monroe A., The effect of heat treatment on the microstructure and tensile properties on an HPDC marine transimission, Metals 11, 517, 2021, 1-17.
[3] Fortini, A., Lattanzi, L., Merlin, M. et al. Comprehensive Evaluation of Modification Level Assessment in Sr-Modified Aluminium Alloys. International Journla of Metalcasting 12, 697–711, 2018.
[4] Ibrahim M. F., Elgallad E. M., Valtierra S., Doty H. W., Samuel F. H., Metallurgical parameters controlling the eutectic silicon characteristics in Be-treated Al-Si-Mg alloys, Materials 9, 78, 2016, 1-17.
[5] Li R. X., Li R. D., Zhao Y. H., Li C. X., Sun X. F., Guan H. R., Hu Z. Q., Effect of heat treatment on eutectic silicon morphology and mechanical properties of Al-Si-Cu-Mg cast alloys, Transactions of Nonferrous Metals Society of China 14, 2004,496-500.
[6] Apelian D., Shivkumar S., Sigworth G., Fundamental aspects of heat treatment of cast Al-Si-Mg alloys, AFS Trans. 97, 1989, 727–742.
[7] Roy E. L., Castings, 9th Ed, ASM International: Materials Park, OH, USA, 1992, vol. 15, pp. 743-769.
[8] Chen R., Xu Q., Guo H., Xia Z., Wu Q., Liu B., Correlation of solidification microstructure refining scale, Mg composition and heat treatment conditions with mechanical properties in Al-7Si-Mg cast aluminum alloys, Materials Science and Engineering: A, vol. 685, 2017, pp. 391-402.
[9] Zhang D. L., Zheng L. H., StJohn D. H., Effect of a short solution treatment time on microstructure and chemical properties of modified Al-7wt.%Si-0.3wt.%Mg alloy, Journal of Light Metal, 2002, 27-36.

TORNA ALL'INDICE >