Visual Abstract

On the peak strength of 7050 aluminum alloy: mechanical and corrosion resistance

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ABSTRACT. This work consists of an experimental study on the ageing response and resulting properties of AA7050 plate material. New heat treatments are investigated for achieving a peak-aged temper, as a T6 temper may be said to be, that achieves yield and tensile strengths superior to those of the documented T7 treatments. For this alloy, the Standard establishes T7X tempers which were developed to obtain a very good compromise between mechanical strength and corrosion resistance. Nevertheless, for all those applications in which the environment is not considered critical for corrosion behaviour, the peak strength condition could be beneficial. In this experimental work, the authors use standard hardness testing to investigate mechanical response as a function of ageing time at several ageing temperatures, all applied immediately after solution. Upon identifying specific times and temperatures of interest, specimens aged under the selected treatments were subjected to tensile testing and intergranular corrosion testing. The results show that a single-step ageing heat treatment is able to produce a significantly high both yield and ultimate tensile strength. Moreover, the corrosion test data indicates that this new heat treatment produces corrosion resistance similar to that of the T76 heat treatment.

KEYWORDS. Aluminum Alloys; AA7050; Heat treatment; Mechanical strength; Corrosion.

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INTRODUCTION

The 7xxx series aluminum alloys are heat treatable alloys based on the Al−Zn−Mg (−Cu) system and they are widely used in high performance structural aerospace and transportation applications. Together with the chemical composition and the fabrication process, their properties are significantly influenced by the heat treatments:

precipitation hardening provides one of the most widely used mechanisms for the strengthening of light alloys. This process involves three basic steps: solution treatment, quenching and ageing, where the peak hardening condition is achieved thanks to phases nucleating at precise treatment times and temperatures. Depending on the chemical composition, the precipitation sequence can be very complicated and can involve many stable and/or metastable compounds. For the 7xxx alloys, the possible existing phases depend on the Mg/Zn ratio and include Guinier-Preston zones (GP zones), metastable precipitates T′ and η′, stable precipitate η ($Mg(Al,Cu,Zn)_2$) and T ($(Al,Zn)_{49}Mg_{32}$). It is well known that when the Mg/Zn ratio is between 0.15 and 0.4, η′ and η precipitates appear, whereas for Mg/Zn ratios between 0.5 and 6, T phase appears [1, 2, 3]. In 7xxx alloys containing copper, θ (Al_2Cu) and S (Al_2CuMg) phases can also be present [4, 5].
In recent years, several studies were proposed to increase both the strength and corrosion resistance of 7xxx alloys, such as retrogression and reageing (RRA) [6, 7], step-quench and ageing treatment [8] and some other thermomechanical treatments [9]. For increasing the corrosion resistance while keeping the strength levels similar to T6 temper, Park et al. [10] proposed the RRA and a new two-step ageing process was introduced by Wang et al. [11] to achieve higher stress corrosion cracking resistance and strength. Peng et al. [12] proposed that the dual-RRA could further improve stress corrosion cracking (SCC) resistance with retention strength comparable to RRA temper. Several studies were also published investigating the effect of ECAP (Equal Channel Angular Pressing) in grain refinement and its combination with age hardening in achieving superior strength [13, 14, 15].
For achieving excellent mechanical properties and satisfactory corrosion resistance of 7050 alloy, non-isothermal ageing was proposed by D. Jiang et al. [16], the effect of the size and distribution of precipitates on stress corrosion cracking of 7050 alloy was clarified in [17] and the effect of homogenization on corrosion resistance of extruded bars was intensively studied in [18]. The relationships between microstructure, i.e. the nature, density and size of precipitates, and corrosion properties was also deeply investigated in [19]. Nevertheless, it is well known [1, 2, 3] that 7xxx aluminum alloys are more susceptible to intergranular corrosion (IGC) in the one step T6 temper than in the two step T7 temper and in [20], the role of the grain boundary precipitates was extensively clarified.
For most engineering applications, a good compromise between mechanical properties and corrosion resistance is usually required. In this sense the content of ASTM B918/B918M standard [1] will be considered that, for the 7050 aluminum alloy, suggests only the overaged two-step ageing T7x tempers, thereby assuring good corrosion performance but an out-of-peak strength condition. Nevertheless, in the applications in which corrosion behaviour does not have a primary role, for example in the space industry (for satellites and space vehicles), in the fabrication of plastic moulds and generally in all those situations in which the components are painted or coated, the maximization of the alloy's strength can be an important achievement.
The aim of this work is to study the peak strength condition for a single-step T6 heat treatment. In this experimental work, the authors use standard hardness testing to investigate mechanical response as a function of ageing time at several ageing temperatures, all applied immediately after solution. Upon identifying specific times and temperatures of interest, specimens aged under the selected treatments were subjected to tensile and corrosion testing.

EXPERIMENTAL PROCEDURE

In this work a 7050 T7451 aluminum alloy plate 100 mm thick was investigated after solution treatment followed by different ageing conditions. The nominal chemical composition is reported in Tab. 1.

% Zn	% Mg	% Cu	% Zr	% Al
6.21	2.10	2.19	0.10	Bal.

Table 1: Nominal chemical composition of the alloy investigated.

From the plate, samples for the hardness, tensile and corrosion tests were machined. A solution treatment was performed on each specimen at 477°C for 60 minutes according to the ASTM B918/B918M standard [1] and ageing treatments at different temperatures were carried out (Tab. 2). Both the solution and the ageing treatments were performed in a laboratory furnace.
In the ASTM B918/B918M standard, the initial condition before ageing is 'W51', i.e. stress-relieved by cold stretching to a permanent set of 1.5 to 3 % in the solution heat-treated condition. Since it is not possible to reach this condition in the laboratory tests, after the standard ageing treatment the samples were designated as T76 rather than T7651.

ID	Details
T76	(W) + 121°C x 4.5h + 166°C x 13.5h
121	(W) + 121°C x 0.5h-96h
140	(W) + 140°C x 0.5h-162h
166	(W) + 166°C x 0.5h-48h

Table 2: Scheme of the different heat treatment conditions.

The ageing response was studied using hardness tests (HBW 2.5/62.5 according to the BS EN ISO 6506-1 standard [21]) at different ageing times. Then, tensile tests were performed on specimens aged at times and temperatures selected on the basis of the hardness curves. These specimens were machined in the long transverse (LT) direction of the original plate. The tensile tests were carried out according to the ASTM B557M-15 standard [22] on circular cross section specimens (∅ 9mm) using an INSTRON 4507 tensile testing machine.
Finally, intergranular corrosion tests were performed on 20 x 20 x 10 mm^3 samples treated with the same parameters used for the tensile specimens. According to the ASTM G110-92 standard [23], the testing solution consists of 57 g of sodium chloride and 10 ml of hydrogen peroxide diluted to 1 litre with reagent water. In order to quantify and compare the corroded specimens, an analysis was carried out according to the method already described in [24]. In technical literature several methods are available for evaluating the intergranular corrosion behaviour, such as in [25]. The authors followed the ASTM G110-92 standard [23], which is the reference Standard used for engineering applications.
As described in [24], referring to Fig. 1, each pit can be characterized by its roundness, depth and width according to Eqn. (1).

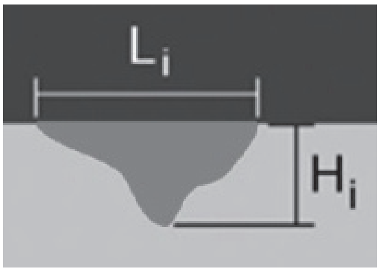


Figure 1: Image analysis of a corrosion pit.

$$R_i^* = R_i \frac{H_i}{L_i} \qquad (1)$$

where $R_i = P_i^2/4\pi S_i$, R_i^* is called the modified roundness and R_i, P_i and S_i are the roundness, the perimeter and the area of the i-th defect respectively. When R_i^* increases, the local notch effect increases.
In order to evaluate the overall effect of multiple corrosion pits, the corroded surface C_S was defined as the ratio between the total length of the defects and the total length of the original profile.

$$C_S = \frac{\sum_i L_i}{L_{tot}} \cdot 100 \qquad (2)$$

where L_i is the length of the i-th corrosion pit and L_{tot} is the observed total length of the original profile (with no corrosion pits).
Finally, a parameter describing the overall surface condition is reported in Eqn. (3):

$$R_c = R^* \cdot C_S \qquad (3)$$

where R^* is the average of the modified roundness values R_i^*.
Twenty images per condition were examined.
The orientation of the specimens in respect to the rolling direction was selected carefully. Since it is known [2] that the ST direction is the one with the weakest corrosion resistance, the 10 mm thick specimens were aligned with such rolling direction. The largest surface, 20 x 20 mm², laid in the L-LT plane, was the reference surface during the exposure in the testing solution. The specimens were immersed in the corrosive solution for 24 hours and at the end of the test, they were cut along the L-ST plane in order to observe the corrosion pits developed in the ST direction. A scheme of the described procedure is reported in Fig. 2.

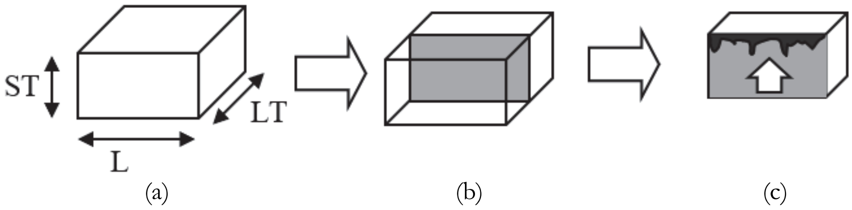


Figure 2: Procedure for the analysis of the corroded profiles. (a) Sample to be immersed in the testing solution; (b) cut along the LT-ST plane; (c) corroded profile observed.

RESULTS AND DISCUSSION

Ageing response

One important aim of this work is to determine the ageing condition able to give peak strength conditions. For this reason, three ageing temperatures, i.e. 121°C, 140°C and 166°C, were selected in order to cover the whole temperature range reported in ASTM B918/B918M. As described in Tab. 2, hardness tests were performed varying the ageing time in order to study the precipitation response. The results obtained are reported in Fig. 3.

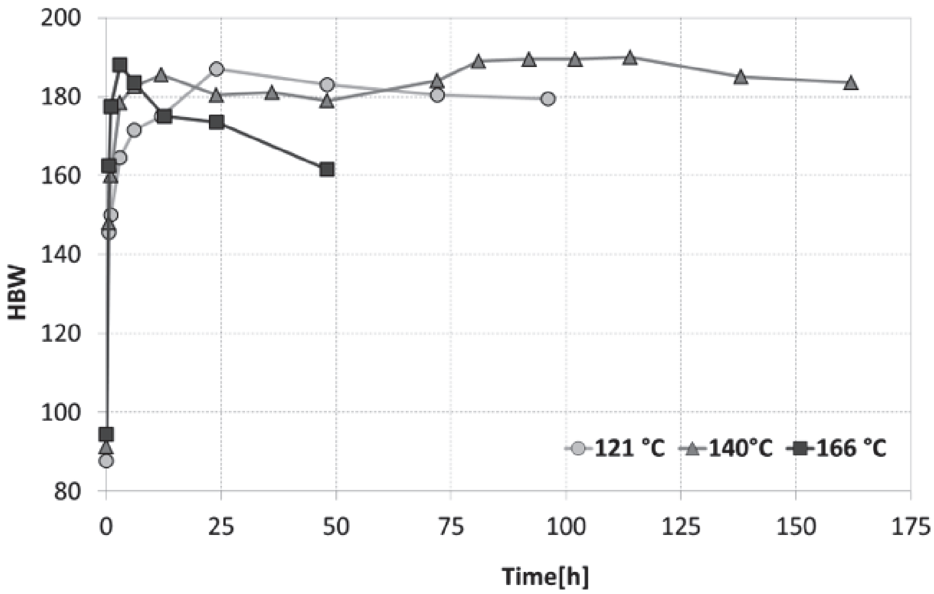


Figure 3: Hardness curves at different ageing temperatures, varying the soaking time.

As expected [2], the precipitation rate increases as the ageing temperature increases. The heat treatments performed at 121°C and 166°C showed a continuous hardness increase until the peak condition, then over-ageing occurred and the corresponding hardness decreased. The ageing tests at 140°C showed a different behaviour, because, after the first hardness peak, a second peak was observed for longer soaking times.
In Tab. 3, the ageing times at peak hardness are summarized.

Ageing temperature	Ageing time at peak hardness	Peak hardness
121°C	24h	186 HBW
140°C	12h (1st peak) 81h (2nd peak)	187 HBW (1st peak) 189 HBW (2nd peak)
166°C	3h	188 HBW

Table 3: Peak hardness and peak hardness times for the ageing temperatures investigated.

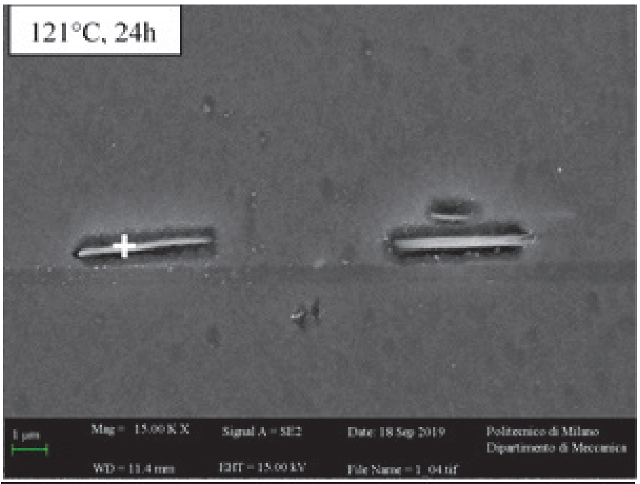
It is well known from the technical literature [2, 3, 6, 26, 27, 28] that in the Al – Zn – Mg (-Cu) system, in the temperature range of 120°C – 130°C, there is a response to hardening due to the precipitation of GP zones and η′ phase. At higher temperatures, 160°C – 170°C, η′ and η phases precipitate [26, 27, 28]. These phases can also contain increasing contents of copper if its amount is higher than 1% in the alloy [19]. It is well known [20] that η′ and η phases improve corrosion resistance, especially stress corrosion cracking and this result is further enhanced by the presence of copper in the previous compounds. By observing the TTT curve for 7xxx alloys published in the technical literature [26, 27, 28], the first peak observed during the tests at 140°C is associated with the precipitation of GP zones and η′ and the second peak is associated with the nucleation of η phase.

As described in the technical literature [2, 3, 26], the η′ precipitates are plate-shaped particles, whereas η precipitates can assume a plate, rod or lath shape. Sha et al. [26] reported that the chemical composition of precipitates can involve different amounts of Zn, Cu and Mg, i.e. the Zn/Mg ratio for such phases increases as the ageing time increases starting from a Zn/Mg ratio ~ 1 for GP zones up to a Zn/Mg ratio equal to about 1.2-1.3 for η′ precipitates and higher values for η precipitates.

After the standard metallographic preparation, the specimens were etched using Keller reagent and the phases observed were investigated using a scanning electron microscope (SEM) and EDXS (Energy Dispersion X-Ray System).

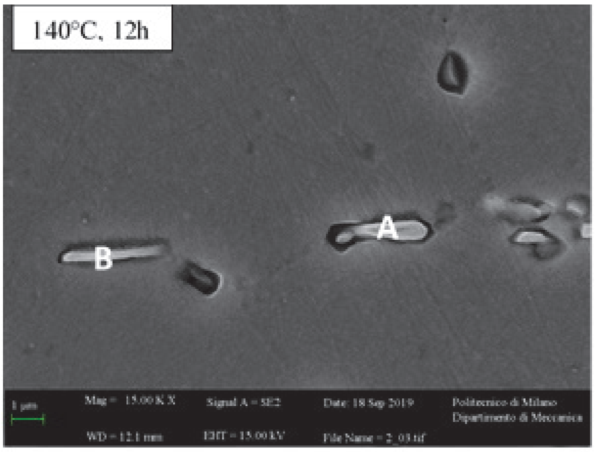
Fig. 4 shows an example of the precipitates observed and their relative EDXS analysis.

The Zn/Mg ratios show values compatible with those found in technical literature for η′ and η precipitates, as reported in [26]. The presence of copper, on the other hand, can be related to the GP zones that anticipate the formation of η′ and η precipitates. Some authors, in fact, found copper percentages up to 12 at% [26].



Mg [at %]	Cu [at %]	Zn [at %]	Zn/Mg
1.91	4.10	2.47	1.29

a)



	Mg [at %]	Cu [at %]	Zn [at %]	Zn/Mg
A	2.20	3.01	2.69	1.22
B	2.18	1.39	2.80	1.28

b)

Figure 4: Zn-Cu-Mg rich precipitates observed after different ageing times.

TENSILE TESTS

In order to determine the mechanical strength of the alloy at the peak hardness conditions described in Tab. 3, new specimens were machined from the as delivered plate in the LT direction. After the solution treatment and ageing, tensile tests were carried out. Besides the specimens aged in the non-standard conditions described in Tab. 3, it was decided to prepare some samples in the T76 temper as well, according to the time-temperature cycle described in the ASTM B918/B918M standard.
The comparison between the results obtained is shown in Figs. 5 and 6.

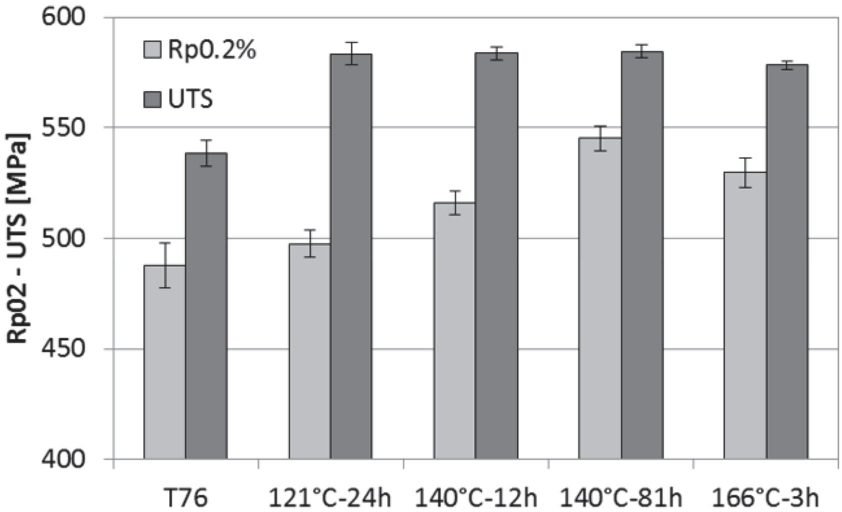


Figure 5: Comparison between the yield and UTS values obtained.

From the mechanical strength point of view, all the non-standard treatments resulted in higher yield and UTS values compared to the T76 temper. Among the non-standard conditions, the best performance was obtained by the specimens treated at 140°C for 81 hours: as shown in Fig. 5, the UTS value was comparable with the others, but the yield stress was remarkably higher. In terms of the percentage elongation and the reduction of area, no appreciable differences were detected among the ageing conditions tested.

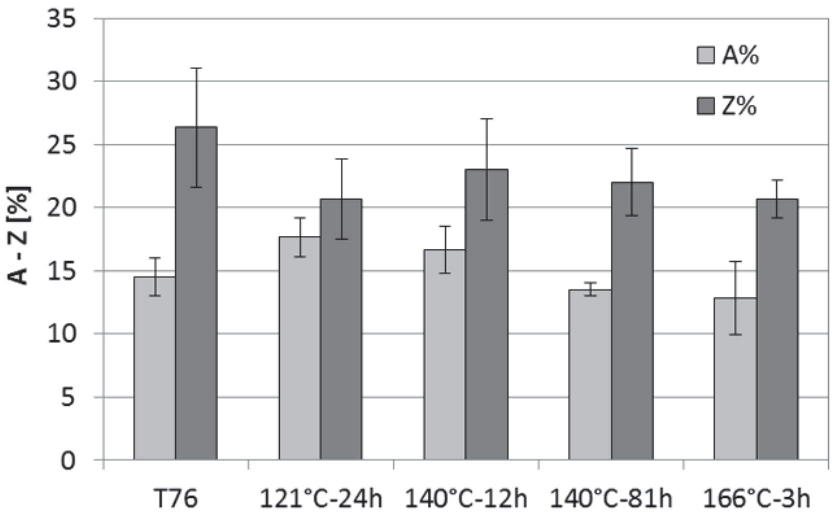


Figure 6: Comparison between the percentage elongations (A%) and the reductions of area (Z%).

INTERGRANULAR CORROSION TESTS

In order to complete the alloy characterization in the ageing conditions investigated, intergranular corrosion tests were performed according to the ASTM G110-92 standard. In Fig. 7, some of the corrosion pits observed are shown.

Applying the procedure described previously, the corrosion damages were quantified and compared with the T76 treatment. In Fig. 8, the modified roundness (*R**) was plotted against pit area values for different ageing parameters and compared with T76 temper. The results show that only the samples treated at 140°C-81h has a behaviour similar to that of T76.

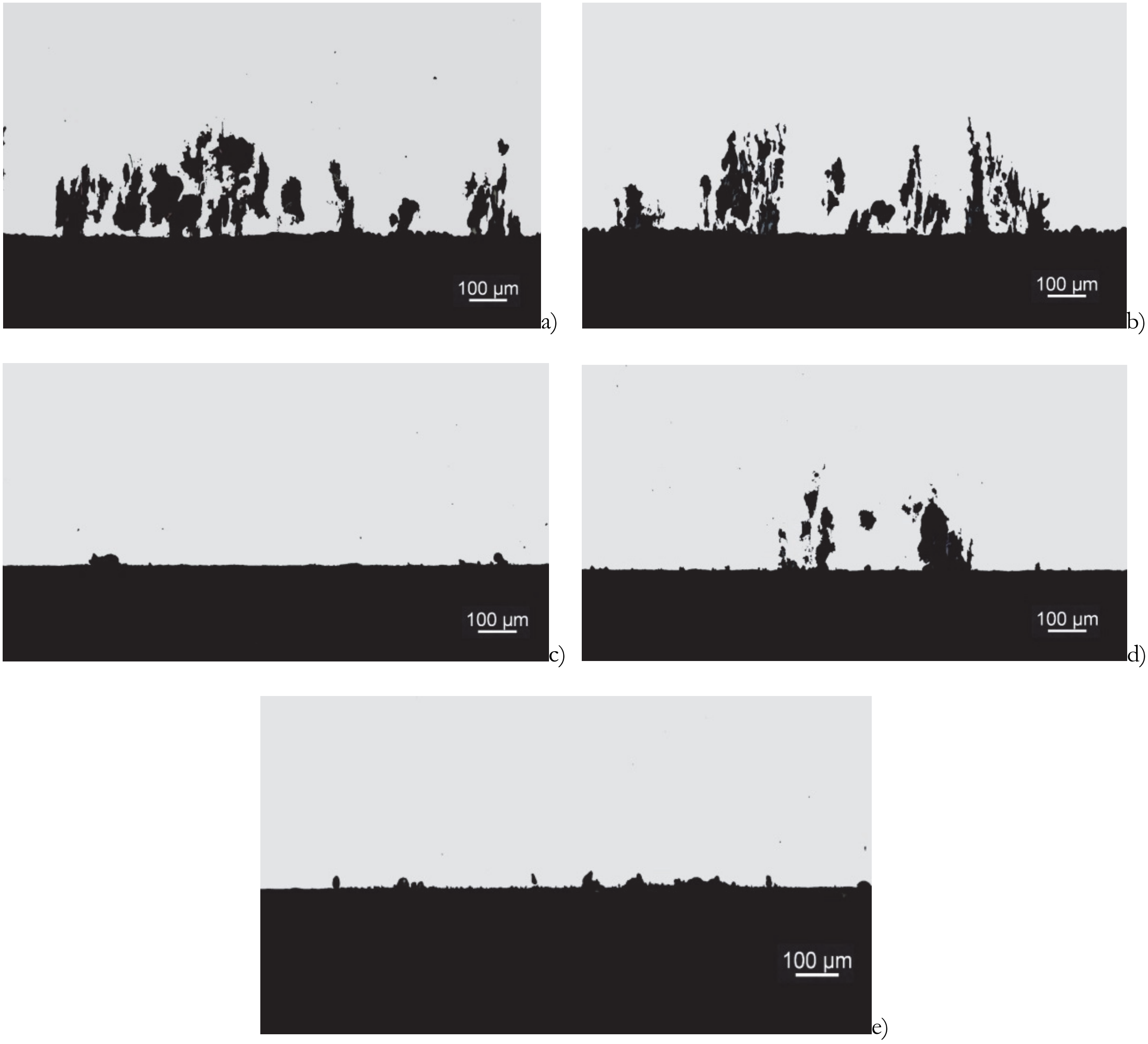


Figure 7: Results of intergranular corrosion tests in samples with different ageing parameters – a) 121°C, 24h; b) 140°C, 12h; c)140°C, 81h; d) 166°C, 3h; e) T76.

In Tab. 4 all the corrosion parameters associated with the investigated specimens were summarized. The results confirm that the one step ageing at 140°C, 81h has similar corrosion behaviour to the two step ageing T76 temper. Park et al. [10] published TEM studies on retrogression and reageing (RRA) of AA7075, a closely related material. This work suggests conversion of η' precipitates to η, particularly at grain boundaries, which may be responsible for the improved corrosion resistance imparted by the RRA heat treatments to AA7075. This is also confirmed in [29].

The presence of the more stable η precipitates after one step ageing at 140°C, 81h, confirmed by the TTT curve, is in agreement with the good corrosion resistance of the new heat treatment.

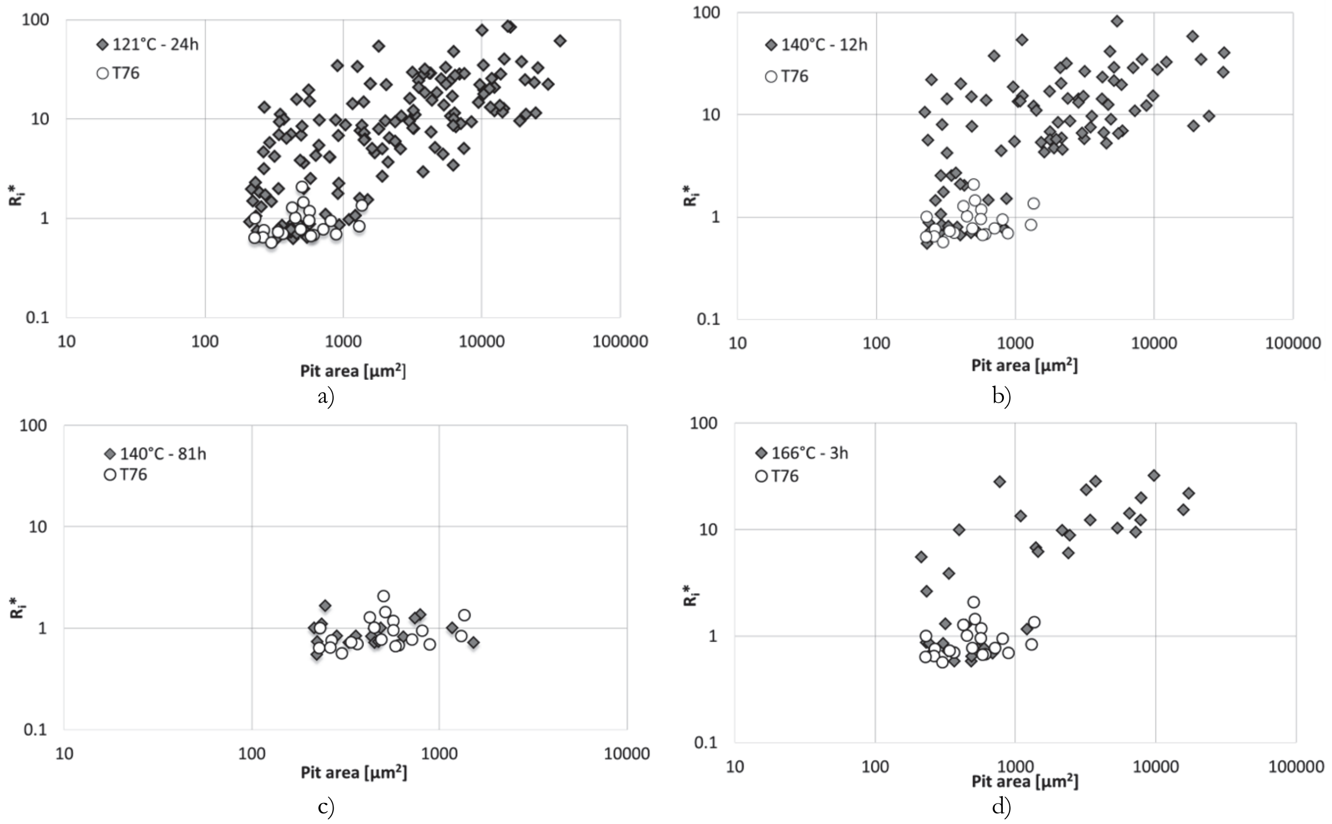


Figure 8: Modified roundness vs pit area for different ageing parameters compared with T76 temper.

	121°C – 24h	140°C – 12h	140°C – 81h	166°C – 3h	T76
R^*	13.8	13.8	1.3	10.0	1.1
C_s	44.0	26.6	2.1	9.4	3.4
R_c	609.4	371.7	2.8	95.3	3.2

Table 4: Comparison of the corrosion resistance for the ageing conditions investigated.

The mechanical and the corrosion characterization of the alloy described in the previous paragraphs represents a clear overview of the alloy performances varying the heat treatment conditions. Such information is useful for the designer to suggest the best solution for a specific application. The aging parameters resulted in the best mechanical and corrosion properties are 140°C for 81h. Nevertheless, other aging conditions were considered and characterized from mechanical and corrosion points of view. They represent possible choices for the designer on the base of a cost/benefit analysis.
From metallurgical point of view, the high mechanical strength, particularly the yield stress, obtained after long soaking at 140°C is related to the precipitate resistance to the dislocation motion. It is well known that the highest pinning effect is obtained with specific particle size: small precipitates are too week, whereas coarse precipitates are less effective because of the larger spacing among them. The particle size and distribution are function of the temperature and of the aging time [2, 3]. The results of the tensile tests suggest that at 140°C the precipitation condition is not enough effective when the soaking time is equal to 12h, but when the treatment time increases, the slight coarsening of the existing precipitates, η′, and the nucleation of the η phase create a very efficient obstacle to dislocation movement. The precipitate type, size and distribution influence the corrosion resistance as well. As reported in the previous paragraphs, coarser η precipitates are associated to a higher corrosion resistance. This is confirmed by the corrosion tests on the specimens aged at 166°C. At 140°C, the formation of such phase, together with the precipitate coarsening occurring after long soakings, explain the good corrosion resistance observed after 81h. The technical literature [30, 31, 32] states that the precipitate coarsening increases the particles inter-spacing, reducing the anodic tunnel effect at grain boundary and the electrochemical potential difference among the

matrix and the grain boundary. Summarizing, the temperature of 140°C proved sufficiently high to activate both the precipitate types and to obtain an increase of the inter-spacing, but not too high to result in an excessive particle coarsening with consequent decrease of the mechanical resistance. Further investigation of aging temperatures close to 140°C is hence justified by the possibility to reduce the soaking time necessary to get maximum mechanical and corrosion resistance.

CONCLUDING REMARKS

This experimental work aimed to find the peak strengthening condition for AA7050 by developing out-of-standard ageing times and temperatures.

- ✓ The analysis of the obtained results revealed a very good behaviour of all the non-standard ageing conditions, especially the specimens aged at 140°C, 81 hours. If compared with the standard T76 temper, the ageing at 121°C - 24h, 140°C - 12h, 140°C - 81h and 166°C - 3h showed a yield stress increase of about 2%, 6%, 11% and 8% respectively.
- ✓ The intergranular corrosion tests performed on samples treated at the peak strength condition were analysed using a suitable procedure able to quantify the observed defects. Among the non-standard treatments, only the one at 140°C, 81h showed a very good behaviour, comparable to that for the standard T76 temper.
- ✓ Considering the overall performance of the materials tested, ageing at 140°C for 81 hours showed the best combination of mechanical strength and corrosion resistance. This is consistent with the technical literature which suggests the presence of η precipitates.

Future development of this experimental work will be a deeper study of the ageing temperature of 140°C, with other mechanical (fatigue and toughness) and stress corrosion cracking tests. Furthermore, ageing temperatures close to the 140°C will be investigated by means of dilatometric and calorimetric techniques.

The raw/processed data required to reproduce these findings cannot be shared at this time due to technical or time limitations.
The authors certify that they have NO affiliations with or involvement in any organization or entity with any financial interest (such as honoraria; educational grants; participation in speakers' bureaus; membership, employment, consultancies, stock ownership, or other equity interest; and expert testimony or patent-licensing arrangements), or non- financial interest (such as personal or professional relationships, af filiations, knowledge or beliefs) in the subject matter or materials discussed in this manuscript

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