Study on three-stage T6I6 aging technology to improve the mechanical properties of B95 aluminum alloy

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ABSTRACT

In this article, a study on the three-stage T6I6 aging technology is conducted to improve the mechanical properties of B95 aluminum alloy. After annealing and quenching, B95 aluminum alloy samples were aged in three stages (T6I6) according to four different regimes. Additionally, the authors investigated the traditional T6 artificial aging technology as a basis for comparison with the three-stage T6I6 aging treatments. Based on the results from hardness measurements, tensile testing, optical microscopy, FE-SEM, and electrical conductivity measurements, it was found that the three-stage T6I6 aging treatments achieved a higher density of intermetallic phase precipitates and improved mechanical properties (hardness, tensile strength, and yield strength) compared to the T6 aging technology. The optimal T6I6 aging process is determined as follows: first stage at 130 ºC for 1 hour, second stage at 95 ºC for 10 hours, and third stage at 130 ºC for 20 hours, resulting in a hardness of 185 HV, tensile strength approximately 9.1% higher, yield strength approximately 23.5% higher, and elongation approximately 1.83 times greater than those of the quenching and artificial aging process per ГОСТ 21488-97 standards.

Keywords: B95 aluminum alloy; T6 treatments; T6I6 treatments; Three-stage aging.

1. INTRODUCTION

Nowadays, as the pace of aluminum production accelerates significantly, the position of this metal material has risen to second place after steel. The production and application demand for aluminum compared to other structural metals are continuously increasing. The main advantages of aluminum include its low specific weight, high specific strength, excellent electrical and thermal conductivities, and good corrosion resistance in various environments. Therefore, when aluminum alloys are used as structural materials, they exhibit significant advantages. [1]

B95 aluminum alloy is an Al-Zn-Mg-Cu system alloy, classified as a heat-treatable wrought aluminum alloy. Its chemical composition, according to the Russian standard (ГОСТ 4784-97), includes: (5.0-7.0)% Zn, (1.8-2.8)% Mg, (1.4-2.0)% Cu, with the remainder being Al. [2]

Globally, studies on the T6I6 aging process [3-7] have been published, but applying these processes to actual production conditions in Vietnam has not been entirely suitable, as the three-stage aging duration is excessively long (over two weeks). Domestically, there have been studies on the T6I6 process, but these are limited, and no specific studies on this process have been conducted. Therefore, the research team has investigated the three-stage T6I6 aging process for B95 aluminum alloy (using four modes with changes in temperature and time). Additionally, the team also studied the traditional T6 aging process (using the same batch of samples) to compare with the T6I6 process, thereby providing further evaluation of this method. Based on the results of microstructure, hardness, strength, ductility, and electrical conductivity analyses, the authors developed the T6I6 aging process for the B95 aluminum alloy produced by the Z127 Factory.

2. EXPERIMENTS

2.1. Preparation of research samples

The initial billet was B95 aluminum alloy rolled into 5 mm thick sheets, which were then cut into 129 samples with dimensions of 150 × 150 mm for experimental investigations and 8 standard-sized samples (according to TCVN 197-1:2014 [8]) for tensile testing (figure 1). After cutting, the samples provided by Z127 Factory were subjected to annealing at 415 °C for 2.5 hours [9], followed by quenching at 470 °C for 120 minutes. Traditional T6 aging (130 °C for 40 hours with one sample taken every 2 hours for microstructure and hardness analysis, figure 2) and T6I6 aging were then investigated under four modes as follows:

+ *T6I6 Aging (Mode I):* The samples underwent first-stage aging at 130 °C for 1 hour, second-stage aging at 95 °C for 10 hours, and third-stage aging at 130 °C for 36 hours. A sample was taken every 2 hours to survey the structure and hardness.

+ *T6I6 Aging (Mode II):* The samples underwent first-stage aging at 130 °C for 1 hour, second-stage aging at 80 °C for 24 hours, and third-stage aging at 115 °C for 50 hours. A sample was taken every 2 hours to survey the structure and hardness.

+ *T6I6 Aging (Mode III):* The samples underwent first-stage aging at 130 °C for 1 hour, second-stage aging at 95 °C for 10 hours, and third-stage aging at 115 °C for 46 hours. A sample was taken every 2 hours to survey the structure and hardness.

+ *T6I6 Aging (Mode IV):* The samples underwent first-stage aging at 130 °C for 1 hour, second-stage aging at 80 °C for 24 hours, and third-stage aging at 130 °C for 36 hours. A sample was taken every 2 hours to survey the structure and hardness.

Figure 1. *B95 aluminum alloy samples used for experimental investigations.*

The T6I6 aging process is a three-stage aging procedure, with the first stage at temperature Ta, the second stage at temperature Tb (approximately 25-65 °C), and the third stage at temperature Tc, where Tc ≤ Ta [5]. The research team investigated by fixing the first-stage aging at 130 °C, the second-stage aging at 80 °C and 95 °C (choosing a temperature higher than 65 °C to shorten the duration of the second stage), and the third-stage aging at 130 °C (equal to the first stage temperature) and 115 °C (lower than the first stage temperature) [3, 5, 10, 11].

2.2. Equipment and research methods

The research team utilized the following methods and equipment:

1) Optical Microscopy (OM): The equipment used for this method was the Axio Imager A2M microscope, manufactured in the Federal Republic of Germany.

2) Vickers Hardness Measurement: This was performed on the Wilson Wolpert 432SVD Vickers hardness tester, using the HV10 scale.

3) Tensile Testing: The equipment used was the Devotrans tensile testing machine.

4) Field Emission Scanning Electron Microscopy (FE-SEM): The equipment used was the Tescan Mira microscope.

5) Electrical Conductivity Measurement: The device used was the Megger DLRO 10 (UK). The samples were prepared as follows: T6, T6I6 Mode I, and T6I6 Mode IV each included 2 samples; T6I6 Mode II and T6I6 Mode III each included 1 sample. A total of 8 samples, with dimensions of 125 × 30 × 5 mm, were measured for electrical conductivity.

3. RESULTS AND DISCUSSION

3.1. Changes in the mechanical properties of B95 alloy with T6 and T6I6 aging technologies

3.1.1. Hardness analysis

The variation in hardness over aging time, or the aging curves for T6 and T6I6 (four modes), is shown in figure 2. The peak hardness values and total aging times are presented in table 1.

Overall, the aging curves for T6 and T6I6 consist of two branches. In the left branch, hardness increases with aging time due to the precipitation process during aging. This process leads to the formation of intermetallic phases, which create lattice distortions and elastic stress fields around the precipitates, thereby impeding dislocation movement and enhancing hardness and strength. In the right branch, hardness decreases with aging time as the precipitates coalesce to reduce the system's free energy. This coalescence increases the size and spacing of the precipitates, making dislocation movement easier, thus reducing hardness and strength.

Comparing Mode I and Mode III, where the first and second aging stages are fixed, and the third-stage aging temperature varies, the corresponding results (185 HV; 31 h) and (185.5 HV; 49 h) show that hardness is nearly the same. However, the higher temperature of the third stage in Mode I (130 °C) compared to Mode III (115 °C) shortens the time required to reach peak hardness. Thus, Mode I is superior to Mode III in terms of time efficiency for achieving similar hardness.

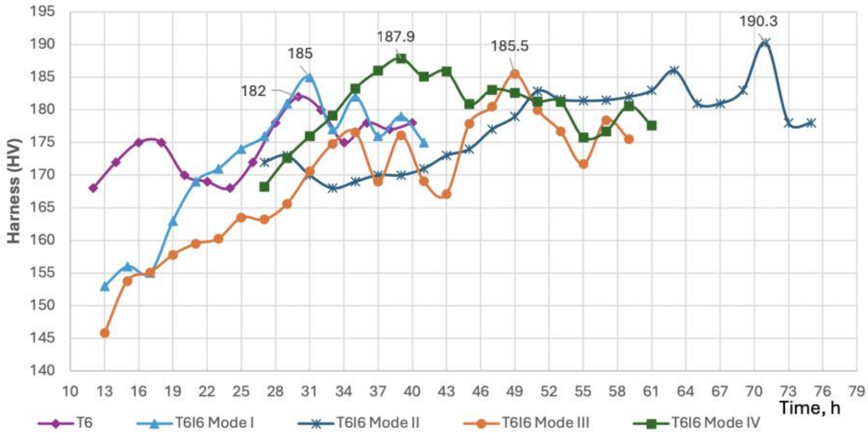


Figure 2. *Aging curves for T6 and the four T6I6 modes.*

Table 1. *Comparison of peak hardness and aging time for different modes.*

Modes	Stage 1	Stage 2	Stage 3	Peak Hardness (HV)	Total Aging Time (h)
T6	130 ºC, 30 h			182	30
I	130 ºC, 1 h	95 ºC, 10 h	130 ºC, 20 h	185	31
II	130 ºC, 1 h	80 ºC, 24 h	115 ºC, 46 h	190.3	71
III	130 ºC, 1 h	95 ºC, 10 h	115 ºC, 38 h	185.5	49
IV	130 ºC, 1 h	80 ºC, 24 h	130 ºC, 14 h	187.9	39

Comparing Mode II and Mode IV, where the first and second aging stages are fixed, and the third-stage aging temperature varies, the corresponding results (190.3 HV; 71 h) and (187.9 HV; 39 h) indicate that a higher third-stage aging temperature leads to a slightly lower peak hardness but significantly reduces the aging time. Although the peak hardness of Mode II is slightly higher than that of Mode IV, the aging time for Mode II (71 h) is relatively long.

Comparing Mode I and Mode IV, where the aging temperatures for the first and third stages are fixed, and the second-stage aging temperature varies, an increase in the second-stage aging temperature shortens the total time to peak hardness (31 h compared to 39 h) but results in a slightly lower peak hardness (185 HV compared to 187.9 HV). Therefore, Modes I and IV are superior to Modes II and III in terms of time efficiency. To choose between Modes I and IV, additional factors such as strength, in addition to hardness and aging time, can be considered for a suitable selection.

3.1.2. Durability investigations

T6 and T6I6 aging (4 modes) were applied to the B95 aluminum alloy, after which these samples were subjected to tensile testing. The results are shown in table 2.

Based on table 2, it can be observed that, in general, aging under the T6I6 mode results in higher tensile strength and yield strength compared to the traditional T6 aging mode and the tensile and yield strength limits specified in the ГОСТ 21488-97 standard [2, 12]. Among the modes, T6I6 Mode II provides the highest tensile strength and yield strength. However, the total aging time for Mode II is 71 hours, which is relatively long and therefore not considered the optimal mode.

Table 2. *Tensile test results for B95 aluminum alloy samples after T6 and T6I6 aging.*

Modes	**F_{max} (N)**	**Relative Elongation, δ (%)**	**Tensile Strength (σ_b, MPa)**	**Yield Strength (σ_{ch}, MPa)**
Quenching and Artificial Aging [2, 12]		7	510	400
T6	22246	13.45	533.5	464
T6I6 Mode I	23199	12.86	556.3	494
T6I6 Mode II	23335	12.26	559.6	496
T6I6 Mode III	22778	13.02	546.2	493
T6I6 Mode IV	22818	13.51	547.2	488

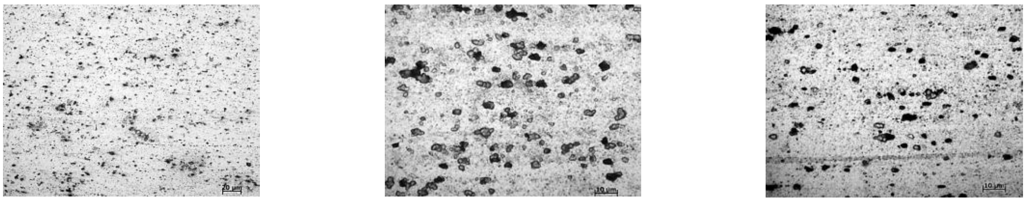
When comparing T6I6 Modes I and IV, the hardness does not differ significantly (as presented in section 3.1.1, but Mode I exhibits higher tensile strength and yield strength than Mode IV. Furthermore, the total aging time for Mode I is 31 hours, which is shorter than the 39 hours required for Mode IV. Comparing T6I6 Mode I with the traditional T6 aging process, Mode I demonstrates better strengthening effects, with higher tensile strength and yield strength, while maintaining a similar aging time to T6. Compared to the quenching and artificial aging modes specified in references [2, 12], T6I6 Mode I achieves approximately 9.1% higher tensile strength, 23.5% higher yield strength, and 1.83 times higher relative elongation.

3.2. Structural changes in B95 alloy with T6 and T6I6 aging technologies

The changes in mechanical properties are explained by the structural transformations during heat treatment. The structural analysis results of the B95 aluminum alloy after T6I6 aging at stages 1 and 2 under different temperatures are presented in figure 3.

The microstructure of the sample after stage 1 aging (130 ºC, 1 h), as shown in figure 3a, indicates the segregation of the supersaturated solid solution after quenching. According to the C-curve (TTT diagram), the primary product of segregation at 130 ºC for 1 hour is the formation of GP zones [9]. (Due to their very small size, in the nanometer range, GP zones cannot be observed with optical microscopy; other methods such as TEM are required for their observation). The purpose of stage 1 aging is the precipitation of primary phases and the creation of nuclei that serve as the driving force for subsequent stage 2 aging.

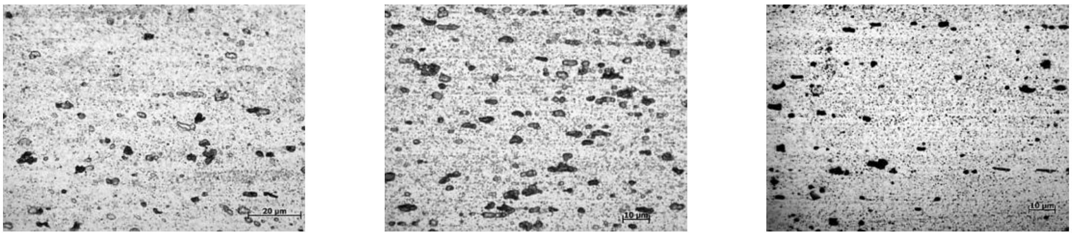
The microstructure after stage 2 aging (figure 3b), with interrupted heating at a temperature of 95 ºC for 10 hours, shows that the precipitation process forms small nuclei of the intermetallic phase. These nuclei appear in greater numbers in the microstructure after stage 2 aging, as shown in figure 3c. Stage 2 aging increases the number of nuclei (both homogeneous and heterogeneous). Heterogeneous nuclei form on the surface of existing nuclei (solid particles) created during stage 1 aging. Homogeneous nuclei form simultaneously with heterogeneous nuclei during stage 2 aging but can appear at arbitrary locations. The formation of heterogeneous nuclei in this case is easier and more favorable compared to homogeneous nuclei. In addition to increasing the number of nuclei, according to the C-curve (TTT diagram), a longer aging time intersects additional lines of various intermetallic phases. In other words, it not only increases the number of nuclei but also the variety of nuclei, such as phases η' and T'[9].



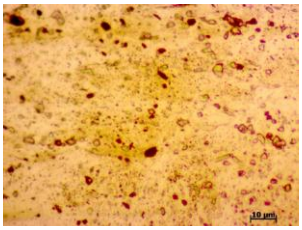
a) Stage 1 (130 ºC, 1 h) *b) Stage 2 (95 ºC, 10 h)* *c) Stage 2 (80 ºC, 24 h)*

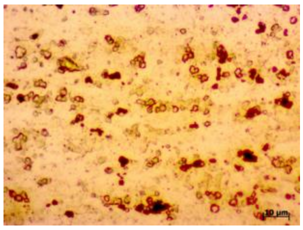
Figure 3. *Microstructure images of B95 aluminum alloy samples after stage 1 and stage 2 aging in T6I6 mode, magnification X500.*

A comparison of the microstructure of the B95 aluminum alloy after completing the T6 and T6I6 modes with total aging time at the point of peak hardness is shown in figure 4.



a) T6 (130 ºC, 30 h) *b) Stage 3 Mode I (130 ºC, 31 h)* *c) Stage 3 Mode II (115 ºC, 71 h)*

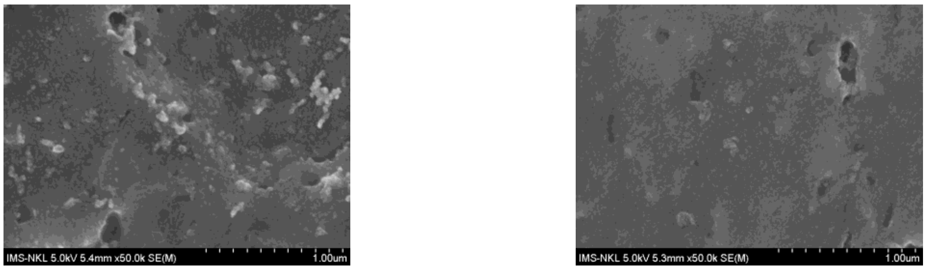




d) Stage 3 Mode III (115 ºC, 49 h) *e) Stage 3 Mode IV (130 ºC, 39 h)*

Figure 4. *Microstructure images of B95 aluminum alloy samples after T6 and T6I6 aging, magnification X500.*

Observing the microstructure images in figure 4, it can be seen that the density of the precipitated phases in all four T6I6 modes is higher than in the T6 mode. This is because the interrupted aging process at stage 2 provided the driving force for stage 3 aging, resulting in intermetallic phases (in both quantity and variety) that are fine and uniformly dispers within the aluminum solid solution matrix. The microstructural analysis results explain why the three-stage T6I6 aging process provides higher tensile strength and yield strength compared to the traditional T6 aging process.



a) T6I6 Mode I, magnification X50000 *b) T6, magnification X50000*

***Figure 5.** FE-SEM images of B95 aluminum alloy samples after T6 and T6I6 mode I aging.*

Comparing the microstructures of the four T6I6 modes in figures 4b, 4c, 4d, and 4e reveals that, in figure 4c, the intermetallic phases are the finest and most evenly dispersed. Consequently, T6I6 mode II has the highest tensile and yield strength. Figure 4b shows that T6I6 mode I exhibits a higher density of precipitated phases, which are finer and more evenly distributed on the aluminum solid solution matrix compared to T6I6 modes III and IV. This explains why mode I achieves higher tensile and yield strength than modes III and IV. In other words, mode I is the most optimal in terms of mechanical properties and total aging time, as shown in table 2.

Visually, the optical microscopy method reveals differences in the quantity of precipitated phases. However, to fully evaluate the fine precipitates formed during T6I6 aging, the research team analyzed the microstructure using the FE-SEM method for T6 aging and T6I6 mode I (optimal aging), as shown in figure 5.

The microstructure in figure 5 shows that samples aged in T6I6 mode I exhibit a higher density of precipitated phases, which are finer and more evenly distributed than those in T6 aging. This is explained by the T6I6 mode includes stage 1 and stage 2 aging, which facilitates the precipitation process during stage 3 aging. The precipitated phases nucleate more easily, the segregation of the supersaturated solid solution occurs more rapidly, the density of precipitated phases becomes higher, and a greater strengthening effect is achieved through the mechanisms of nucleation and growth.

3.3. Investigation of electrical conductivity of B95 aluminum alloy after T6 and T6I6 aging

The density of precipitated phases can be evaluated not only through microstructural images but also by measuring electrical conductivity. The results of the electrical conductivity survey of the B95 aluminum alloy after T6 and T6I6 (four modes) aging are presented in table 3.

***Table 3.** Electrical conductivity measurement results of B95 aluminum alloy samples.*

Aging Technology	Average R (μΩ)	Electrical Conductivity (%IACS)
T6	61.4	33.42
T6I6 Mode I	62	33.1
T6I6 Mode II	63	32.58
T6I6 Mode III	63.9	32.12
T6I6 Mode IV	63.7	32.22

Electrical conductivity is related to electron scattering phenomena, where intermetallic phases act as scattering centers that deflect moving electrons, reducing their mobility. The more intermetallic phases present in the alloy, the greater the electron scattering, which reduces electron mobility and consequently lowers electrical conductivity, as electrical conductivity is directly proportional to electron mobility. The results in table 3 show that the resistance of samples in the T6I6 modes is higher than that of the T6 mode samples, meaning that the electrical conductivity of T6I6 samples is lower. This indicates that the density of precipitated phases in the T6I6 modes is greater than in the T6 mode.

4. CONCLUSIONS

The research team investigated T6 and T6I6 aging technologies (four modes) applied to the B95 aluminum alloy. Based on the mechanical property results, it was observed that the T6I6 aging achieved higher hardness, tensile strength, and yield strength compared to the traditional T6 aging. This is explained through microstructural image analysis and electrical conductivity measurements, which show that the three-stage T6I6 aging process results in a higher density of intermetallic precipitates that are finer and more uniformly dispersed than those in the T6 aging.

T6I6 mode I aging, consisting of stage 1: 130 ºC for 1 hour; stage 2: 95 ºC for 10 hours; and stage 3: 130 ºC for 20 hours (total aging time of 31 hours), achieved a hardness of 185 HV, a tensile strength of 556.3 MPa, a yield strength of 494 MPa, and an elongation of 12.86%. Compared to the quenching and artificial aging [2, 12], T6I6 mode I resulted in a tensile strength approximately 9.1% higher, a yield strength about 23.5% higher, and an elongation approximately 1.83 times greater. Therefore, among the four T6I6 aging modes studied, the three-stage aging technology of T6I6 mode I is the most suitable in terms of mechanical properties and total aging time and can be used as a reference for future research.

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TÓM TẮT

Nghiên cứu công nghệ hóa già 3 cấp T6I6 nhằm cải thiện cơ tính của hợp kim nhôm B95

Trong bài báo này, nghiên cứu công nghệ hoá già 3 cấp T6I6 nhằm cải thiện cơ tính của hợp kim nhôm B95. Mẫu hợp kim nhôm B95 sau khi được ủ, tôi được hoá già 3 cấp T6I6 theo 04 chế độ khác nhau. Ngoài ra, nhóm tác giả cũng khảo sát thêm công nghệ hoá già truyền thống T6 làm cơ sở để so sánh với công nghệ hoá già 3 cấp T6I6. Dựa trên những kết quả thu được từ phương pháp xác định độ cứng, phương pháp thử kéo, phương pháp hiển vi quang học, FE-SEM và đo độ dẫn điện thấy rằng: công nghệ hoá già 3 cấp T6I6 cho mật độ tiết pha liên kim và cơ tính (độ cứng, giới hạn bền kéo, giới hạn chảy) cao hơn công nghệ hoá già T6. Công nghệ hoá già T6I6 phù hợp là hoá già cấp 1: 130 ºC, 1 h; cấp 2: 95 ºC, 10 h; cấp 3: 130 ºC, 20 h cho độ cứng 185 HV, giới hạn bền kéo cao hơn khoảng 9.1%; giới hạn chảy cao hơn khoảng 23.5%; độ giãn dài tương đối cao hơn khoảng 1.83 lần so với công nghệ tôi và hoá già nhân tạo theo tiêu chuẩn ГОСТ 21488-97.

Từ khoá: Hợp kim nhôm B95; Nhiệt luyện T6; Nhiệt luyện T6I6; Hoá già 3 cấp.