

Effect of Heat Treatment on the Hardness of Cast EN AC-43000-F (AlSi10Mg) Aluminum Alloy

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تأثير المعالجة الحرارية على الصلادة لسبيكة الألومنيوم EN AC-43000-F

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Received: July 16, 2026

Accepted: September 27, 2026

Published: October 08, 2026

Abstract:

An Heat treatment is an important method for modifying the mechanical properties of heat-treatable cast aluminum alloys. This study experimentally investigates the effects of annealing and T6 heat treatment on the Rockwell hardness of cast EN AC-43000-F (AlSi10Mg) aluminum alloy. The investigated conditions included the as-cast state, annealing at 350 °C for 1.5 h followed by furnace cooling, solution treatment at 540 °C for 2 h followed by water quenching, and artificial aging at 170 °C for 4, 8, and 12 h. The specimens measured 50 × 40 × 10 mm. Hardness was measured using the Rockwell HRF scale in accordance with ASTM E18. For each heat-treatment condition, three independent specimens were evaluated, and the reported hardness values represent their average. The mean hardness of the as-cast alloy was 64.9 HRF. Annealing reduced the hardness to 52.9 HRF, corresponding to an approximately 18.5% decrease relative to the as-cast condition. Following solution treatment and water quenching, the mean hardness increased to 74.4 HRF. Subsequent artificial aging increased the mean hardness to 91.5, 110.4, and 102.5 HRF after 4, 8, and 12 h, respectively. The highest mean hardness was therefore obtained after 8 h at 170 °C. The subsequent decrease after 12 h is consistent with a transition beyond the maximum age-hardening condition; however, without direct microstructural characterization, it cannot be considered conclusive evidence of over-aging. Overall, the results demonstrate that hardness is strongly dependent on thermal history, with T6 treatment producing a substantial increase compared with the as-cast and annealed states.

Keywords: AlSi10Mg; EN AC-43000-F; heat treatment; T6; artificial aging; Rockwell hardness; precipitation hardening; aluminum alloy.

الملخص

تُعد المعالجة الحرارية وسيلة مهمة لتعديل الخواص الميكانيكية لسبائك الألومنيوم المصبوبة القابلة للمعالجة حرارياً. تبحث هذه الدراسة تجريبياً في تأثيرات كل من التلدين (annealing) والمعالجة الحرارية من النوع T6 على صلادة "روكويل" (Rockwell) لسبيكة الألومنيوم المصبوبة EN AC-43000-F (AlSi10Mg). وشملت الظروف المدروسة: حالة الصب الأولية (as-cast)، والتلدين عند درجة حرارة 350 درجة مئوية لمدة 1.5 ساعة متبوعاً بتبريد داخل الفرن، والمعالجة بالمحلول (solution treatment) عند 540 درجة مئوية لمدة ساعتين متبوعة بالتخميد في الماء (water quenching)، والتقسية الاصطناعية (artificial aging) عند 170 درجة مئوية لمدة 4 و 8 و 12 ساعة. كانت أبعاد العينات 50 × 40 × 10 مم، وجرى قياس الصلادة باستخدام مقياس "روكويل" (HRF) وفقاً للمواصفة ASTM E18. وقد تم تقييم ثلاث عينات مستقلة لكل حالة من حالات المعالجة الحرارية، وتمثل قيم الصلادة المذكورة متوسط هذه القياسات. بلغ متوسط صلادة السبيكة في حالة الصب الأولية 64.9 HRF. وأدى التلدين إلى خفض الصلادة إلى 52.9 HRF، وهو ما يمثل انخفاضاً

بنسبة 18.5% تقريباً مقارنة بحالة الصب الأولية. وبعد إجراء المعالجة بالمحلول والتخميد في الماء، ارتفع متوسط الصلادة إلى 74.4 HRF. كما أدت عملية التقسية الاصطناعية اللاحقة إلى زيادة متوسط الصلادة ليصل إلى 91.5 و 110.4 و 102.5 HRF بعد فترات زمنية بلغت 4 و 8 و 12 ساعة على التوالي. وبناءً على ذلك، تم الحصول على أعلى متوسط للصلادة بعد المعالجة لمدة 8 ساعات عند درجة حرارة 170 درجة مئوية. ويتمشى الانخفاض الملاحظ بعد 12 ساعة مع تجاوز حالة الصلادة القصوى الناتجة عن التقسية (peak-aging condition)؛ ومع ذلك، ونظراً لعدم إجراء توصيف مباشر للبنية المجهرية، لا يمكن اعتبار ذلك دليلاً قاطعاً على حدوث "التقسية المفرطة" (over-aging). وبشكل عام، تُظهر النتائج أن الصلادة تعتمد بشكل كبير على التاريخ الحراري، حيث أدت المعالجة T6 إلى زيادة ملحوظة في الصلادة مقارنة بحالتي الصب الأولي والتلدين.

الكلمات المفتاحية: AlSi10Mg؛ EN AC-43000-F؛ معالجة حرارية؛ T6؛ تعتيق اصطناعي؛ صلادة روكويل؛ تصليد بالترسيب؛ سبيكة ألومنيوم.

1. Introduction

Heat treatment is an important method for improving the mechanical properties of cast aluminum alloys. This study investigates the effect of annealing and T6 heat treatment on the Rockwell hardness (HRF) of cast EN AC-43000-F (AlSi10Mg) aluminum alloy. The treatments include annealing at 350 °C for 1.5 h, solution treatment at 540 °C for 2 h followed by water quenching, and artificial aging at 170 °C for 4, 8, and 12 h. The aim is to evaluate how thermal history affects hardness and to identify the aging condition that gives the highest hardness among those tested.

2. Materials and Methods

2.1. Material and Nominal Chemical Composition

The material investigated in this study was cast EN AC-43000-F aluminum alloy, belonging to the Al-Si-Mg alloy family and commonly designated as AlSi10Mg. The alloy was investigated in the as-cast condition before application of the different heat-treatment schedules.

The nominal chemical composition used for identifying the alloy is presented in Table 1. These values represent the nominal composition range associated with the alloy designation and should not be interpreted as a chemical analysis of the specific specimens unless an independent chemical analysis such as optical emission spectroscopy (OES) or X-ray fluorescence (XRF) has been performed.

Table 1. Nominal chemical composition of EN AC-43000-F (AlSi10Mg).

Element	Nominal composition (wt.%)
Al	Balance
Si	9.0–11.0
Mg	0.20–0.45
Fe	≤ 0.55
Mn	≤ 0.45
Ni	≤ 0.05
Ti	≤ 0.15
Cu	≤ 0.05
Pb	≤ 0.05
Zn	≤ 0.10
Sn	≤ 0.05

The presence of silicon and magnesium makes this alloy suitable for heat-treatment studies because its mechanical response can be modified through thermal processing and precipitation-related mechanisms.

2.2. Specimen Preparation

The specimens were prepared from the cast material using a mechanical reciprocating saw. Continuous water cooling was applied during cutting to minimize heat generation and prevent unintended thermal modification of the material during specimen preparation.

All specimens were prepared to nominal dimensions of $50 \times 40 \times 10$ mm. Maintaining identical specimen dimensions was intended to provide consistent conditions during heat treatment and hardness testing.

2.3. Surface Preparation

Before hardness testing, the test surfaces were manually ground using waterproof abrasive papers in the following sequence: 100P GOLD, 220P, 800P, and 1200P. The purpose of surface preparation was to remove cutting marks and relatively coarse surface irregularities and to obtain a sufficiently flat and uniform surface for Rockwell indentation.

2.4. Heat Treatment Procedures

Heat treatment was carried out using an electric box/muffle furnace equipped with temperature control. The furnace temperature-control accuracy was approximately ± 5 °C. The electric box/muffle furnace used in the heat-treatment experiments is shown in Fig. 1. The investigated heat-treatment conditions are summarized in Table 2.



Figure. 1. Electric box/muffle furnace used for the heat treatment of the EN AC-43000-F specimens.

Table 2. Heat-treatment conditions investigated in the present study.

Condition	Treatment	Temperature	Holding time	Cooling
As-Cast	No heat treatment	—	—	—
Annealed	Annealing	350 °C	1.5 h	Furnace cooling
ST-Q	Solution treatment + quenching	540 °C	2 h	Water quenching
T6-4h	Solution + quenching + artificial aging	170 °C aging	4 h	Air cooling
T6-8h	Solution + quenching + artificial aging	170 °C aging	8 h	Air cooling
T6-12h	Solution + quenching + artificial aging	170 °C aging	12 h	Air cooling

2.4.1. Annealing Treatment

Three specimens were subjected to annealing at 350 °C for 1.5 h. After completion of the holding period, the specimens were allowed to cool slowly inside the furnace. The purpose of this treatment was to investigate the effect of thermal exposure and slow cooling on the hardness of the alloy compared with the original as-cast condition.

2.4.2. T6 Heat Treatment

The T6 treatment consisted of three sequential steps: solution treatment, water quenching, and artificial aging. A total of nine specimens were subjected to the T6 treatment, with three independent specimens assigned to each aging duration.

2.4.2.1. Solution Treatment

The specimens were heated to 540 °C and held at this temperature for 2 h. The solution-treatment step was intended to promote dissolution or redistribution of soluble alloying constituents within the aluminum-rich matrix and establish a suitable condition for subsequent precipitation during aging.

2.4.2.2. Water Quenching

Immediately after completion of the solution-treatment period, the specimens were removed from the furnace and rapidly transferred to a container containing room-temperature water. The transfer time from the furnace to the quenching medium was maintained at approximately 3–5 s using heated-metal tongs. Rapid quenching was employed to retain a supersaturated solid solution and minimize precipitation during cooling before artificial aging.

The specimens immediately after removal from the furnace and prior to water quenching are shown in Fig. 2.



Figure. 2. EN AC-43000-F specimens immediately after removal from the furnace and prior to water quenching.

2.4.2.3. Artificial Aging

Following water quenching, the specimens were subjected to artificial aging at 170 °C. The nine T6 specimens were divided into three groups, each containing three independent specimens: T6-4h (4 h), T6-8h (8 h), and T6-12h (12 h). After completion of the specified aging period, the specimens were removed from the furnace and allowed to cool in air. The three aging durations were selected to represent relatively short, intermediate, and prolonged aging conditions and to enable examination of the evolution of hardness with increasing aging time.

2.5. Hardness Testing

Hardness measurements were performed using an Ernst Hardness Tester manufactured by Prodit S.A.S., Italy. The measurements were conducted using the Rockwell HRF scale, with a 1/16 in. (1.588 mm) ball indenter, a 60 kgf test force, and a 15 s dwell time, following the Rockwell hardness testing principles specified by ASTM E18 [8]. The hardness testing setup is shown in Fig. 3.



Figure. 3. Ernst Hardness Tester used for Rockwell HRF hardness measurements.

The prepared specimen surface was positioned horizontally and supported securely on the testing anvil. For each specimen, three hardness measurements were obtained at separate locations on the prepared surface. The average hardness of each individual specimen was calculated as:

$$\bar{H}_i = \frac{H_{i1} + H_{i2} + H_{i3}}{3}$$

where $\bar{H}_i$ is the average hardness of specimen i , and H_{i1} , H_{i2} , and H_{i3} are the three hardness readings obtained from that specimen.

Because the three specimens within each treatment condition were independent specimens, the final hardness value for each treatment was calculated from the three independent specimen averages:

$$\bar{H} = \frac{\bar{H}_1 + \bar{H}_2 + \bar{H}_3}{3}$$

The results are reported as mean hardness $\pm$ sample standard deviation.

2.6. Data Analysis

For each treatment condition, three independent specimen means were used as the statistical replicates. The sample standard deviation was calculated according to:

$$s = \sqrt{\frac{\sum_{i=1}^n (H_i - \bar{H})^2}{n - 1}}$$

The sample variance was calculated as:

$$s^2 = \frac{\sum_{i=1}^n (H_i - \bar{H})^2}{n - 1}$$

where $n = 3$ is the number of independent specimens for each treatment condition. The percentage change in hardness relative to the as-cast condition was calculated as:

$$\% \Delta H = \frac{\bar{H}_{\text{condition}} - \bar{H}_{\text{as-cast}}}{\bar{H}_{\text{as-cast}}} \times 100$$

The use of $n - 1$ in the standard-deviation and variance calculations is appropriate because the three reported specimen values represent independent experimental replicates rather than three repeated indentations from a single specimen.

3. Results and Discussion

3.1. Hardness Results

The measured hardness values for the investigated conditions are presented in Table 3. The three numerical values associated with each treatment represent the average hardness values of three independent specimens.

Table 3. Rockwell HRF hardness results for the investigated heat-treatment conditions.

Condition	Specimen 1	Specimen 2	Specimen 3	Mean	SD	Variance	Change vs. As-Cast
As-Cast	64.8	64.9	65.1	64.9	0.15	0.02	0.0%
Annealed	55.0	51.7	52.0	52.9	1.82	3.33	−18.5%
ST-Q	73.1	74.3	75.7	74.4	1.30	1.68	+14.5%
T6-4h	92.4	91.8	90.2	91.5	1.14	1.29	+40.9%
T6-8h	111.4	109.8	110.0	110.4	0.87	0.76	+70.0%
T6-12h	101.0	104.1	102.5	102.5	1.55	2.41	+57.9%



Figure 4. Representative Rockwell hardness tester readings for the investigated heat-treatment conditions: (a) As-Cast, (b) Annealed, (c) ST-Q, (d) T6-4h, (e) T6-8h, and (f) T6-12h.

The results demonstrate a pronounced dependence of hardness on heat-treatment condition. The as-cast alloy exhibited a mean hardness of 64.9 HRF. Annealing reduced the hardness to 52.9 HRF, whereas solution treatment followed by water quenching increased the hardness to 74.4 HRF. Subsequent artificial aging produced a further increase, with mean hardness values of 91.5, 110.4, and 102.5 HRF after 4, 8, and 12 h, respectively. The highest mean hardness obtained in the present experimental program was therefore 110.4 HRF after artificial aging at 170 °C for 8 h.

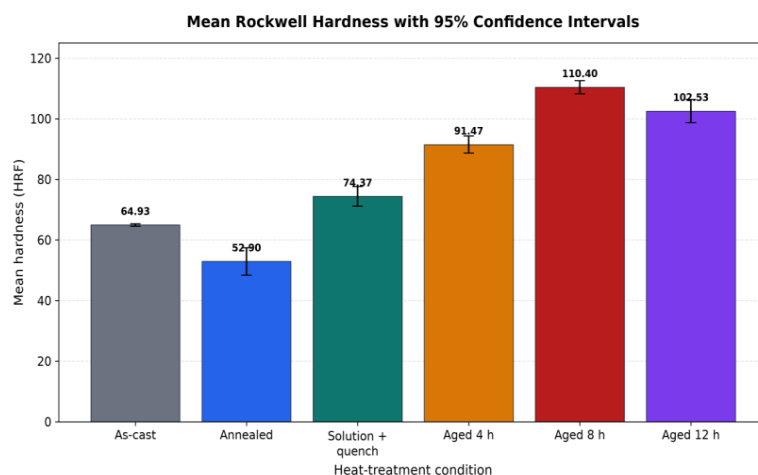


Figure 5. Comparison of mean Rockwell HRF hardness values for the investigated heat-treatment conditions.

3.2. Effect of Annealing on Hardness

The as-cast condition exhibited a mean hardness of 64.9 HRF, while the annealed condition exhibited a mean hardness of 52.9 HRF. Therefore, annealing resulted in an approximately 18.5% decrease in mean hardness. This reduction is consistent with the general effect expected from thermal exposure followed by slow furnace cooling in a heat-treatable aluminum alloy. Annealing can reduce internal stresses and promote microstructural relaxation and coarsening or redistribution of strengthening features, thereby reducing resistance to localized plastic deformation.

The present result should therefore be interpreted primarily as a reduction in hardness following the applied annealing schedule. Although annealing is commonly associated with increased ductility and reduced residual stress, those properties were not directly measured in the present study and therefore no quantitative conclusion regarding ductility can be drawn from the hardness data alone.

The relatively larger standard deviation of the annealed group, 1.82 HRF, compared with the as-cast group, 0.15 HRF, indicates greater specimen-to-specimen variation under this treatment. This variation may be related to the initial microstructural heterogeneity of the cast material and its response to annealing.

3.3. Effect of Solution Treatment and Quenching

Solution treatment at 540 °C for 2 h followed by water quenching increased the mean hardness from 64.9 HRF in the as-cast state to 74.4 HRF, corresponding to an increase of approximately 14.5% relative to the as-cast condition. The increase can be associated with the altered solid-solution state produced by thermal treatment. During solution treatment, soluble alloying constituents can become more uniformly distributed within the aluminum-rich matrix, while rapid quenching retains a supersaturated condition that provides the basis for subsequent precipitation during artificial aging.

3.4. Effect of Artificial Aging Time

Artificial aging produced the largest hardness changes in the present study. The mean hardness increased from 74.4 HRF after solution treatment and quenching to 91.5 HRF after 4 h aging and to 110.4 HRF after 8 h aging, before decreasing to 102.5 HRF after 12 h. The increase from ST-Q to T6-4h was approximately 23.0%, while increasing aging duration from 4 to 8 h produced a further increase of approximately 20.7%. Compared with the as-cast condition, the T6-8h condition was approximately 70.0% harder.

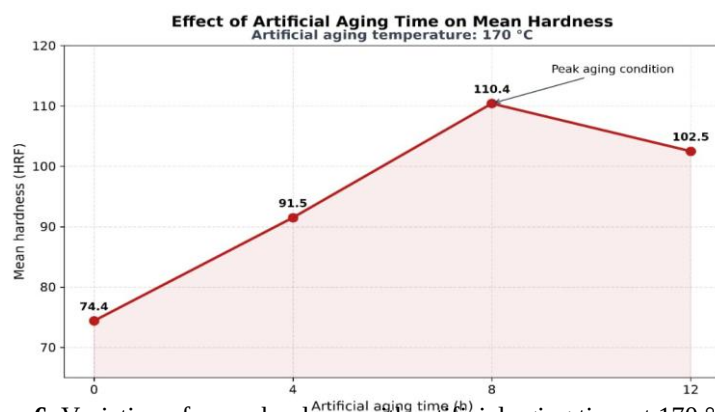


Figure 6. Variation of mean hardness with artificial aging time at 170 °C.

The reduction from 110.4 HRF at 8 h to 102.5 HRF at 12 h corresponds to a decrease of approximately 7.1% relative to the 8 h condition. This behavior indicates that increasing aging time did not continuously increase hardness. Rather, the investigated material reached its highest measured mean hardness at the intermediate aging duration of 8 h, followed by a reduction at 12 h.

Such a trend is consistent with the general concept of age hardening, in which precipitation initially increases resistance to plastic deformation as a favorable population of strengthening precipitates develops, whereas prolonged aging can eventually reduce the strengthening contribution if precipitates coarsen or their strengthening efficiency decreases. However, because direct precipitate characterization was not performed, the decrease at 12 h is described as consistent with a transition beyond the maximum age-hardening condition rather than direct proof of over-aging.

3.5. Metallurgical Interpretation

The observed hardness evolution can be interpreted in terms of the thermal history of the Al-Si-Mg alloy. In the as-cast state, hardness is determined by the as-solidified aluminum-rich matrix, silicon-containing constituents, Mg-Si-related phases, solid-solution effects, and the morphology and distribution of the eutectic structure. During annealing, thermal exposure at 350 °C followed by furnace cooling produced a reduction in hardness. In contrast, solution treatment at 540 °C followed by rapid water quenching produced a higher hardness than the as-cast condition and created the condition required for subsequent artificial aging.

During artificial aging at 170 °C, precipitation-related strengthening processes increase the resistance of the aluminum-rich matrix to localized deformation. The hardness increase from 74.4 HRF after ST-Q to 110.4 HRF after 8 h aging provides experimental evidence that the applied T6 sequence was effective in increasing hardness. The subsequent reduction to 102.5 HRF after 12 h suggests that the strengthening contribution did not continue to increase with aging time. This interpretation is consistent with the precipitation-hardening behavior reported for Al-Si-Mg alloys [2,3], but direct identification of individual precipitate phases would require microstructural characterization.

3.6. Comparison with Previous Studies

The general trend obtained in this work agrees with published research showing that heat treatment can substantially alter the hardness of cast Al-Si-Mg alloys. Neuser et al. [1] demonstrated that both heat treatment and solidification conditions influence the mechanical performance of cast AlSi10Mg. Kuchariková et al. [2] reported differences in hardness associated with heat-treatment-induced microstructural changes in Al-Si-Mg cast alloys. Furui et al. [3] specifically investigated age-hardening behavior in Al-Si-Mg castings and showed that hardness evolves with aging as precipitation processes proceed.

Girelli et al. [6] compared heat-treated additively manufactured AlSi10Mg with corresponding cast alloy and highlighted the influence of manufacturing route on heat-treatment response. Therefore, additive-manufacturing results are used here only as supporting evidence for general heat-treatment mechanisms rather than as direct numerical equivalents for the present cast material. Žaba et al. [7] reported maximum hardness at an 8 h aging condition at 170 °C in their investigated thermal-treatment matrix involving AlSi10Mg. This is consistent with the present observation that 8 h produced the highest mean hardness among the tested durations, but does not imply that 8 h is a universal optimum for all EN AC-43000-F or AlSi10Mg materials.

3.7. Variability and Experimental Repeatability

The standard deviations provide an indication of the repeatability of the hardness response among the three independent specimens in each condition. The as-cast group exhibited the smallest standard deviation, 0.15 HRF, indicating highly consistent hardness values. The T6-8h group also showed relatively low variation, with a standard deviation of 0.87 HRF, despite having the highest mean hardness. The largest standard deviation was observed for the annealed group, 1.82 HRF, followed by the T6-12h group, 1.55 HRF. Because only three independent specimens were used per condition, these values should be interpreted as descriptive measures and broad statistical generalization should be made cautiously.

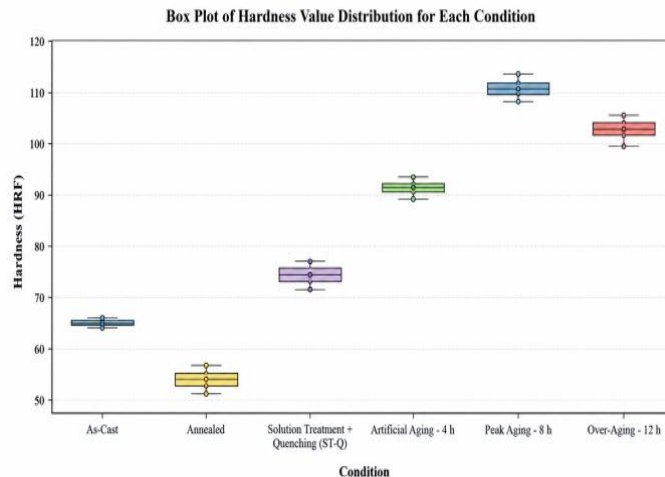


Figure 7. Box plot showing the distribution of individual hardness measurements for each heat-treatment condition.

3.8. Overall Hardness Evolution

The overall hardness sequence obtained in this study was: Annealed < As-Cast < ST-Q < T6-4h < T6-12h < T6-8h, corresponding to mean hardness values of 52.9 < 64.9 < 74.4 < 91.5 < 102.5 < 110.4 HRF. This sequence clearly demonstrates that the thermal history has a substantial influence on the indentation hardness of the investigated EN AC-43000-F alloy. Within the aging range studied, 8 h at 170 °C produced the highest mean hardness, while extending the treatment to 12 h resulted in a measurable reduction.

4. Conclusions

The results showed that annealing reduced hardness from 64.9 HRF in the as-cast state to 52.9 HRF, while solution treatment and quenching increased it to 74.4 HRF. Artificial aging further increased hardness to 91.5, 110.4, and 102.5 HRF after 4, 8, and 12 h, respectively, with the highest value obtained at 8 h. Therefore, T6 treatment significantly improved the hardness of the alloy compared with the as-cast and annealed conditions. The decrease after 12 h suggests a transition beyond peak aging, but microstructural characterization is needed for confirmation.

Compliance with ethical standards

Disclosure of conflict of interest

The authors declare that they have no conflict of interest.

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Nomenclature

Symbol / Abbreviation	Meaning
Al	Aluminum
Si	Silicon
Mg	Magnesium
AlSi10Mg	Aluminum-silicon-magnesium alloy
EN AC-43000-F	Cast aluminum alloy designation
T6	Solution treatment + quenching + artificial aging
ST-O	Solution treatment followed by water quenching
HRF	Rockwell hardness, F scale
SD	Sample standard deviation
s^2	Sample variance
n	Number of independent specimens
H	Hardness value
$\bar{H}$	Mean hardness

Data Interpretation Note

The reported statistical values are based on three independent specimens per treatment condition. The three hardness measurements taken from each specimen were first averaged to obtain one specimen-level value. Therefore, the statistical $n = 3$ used for each treatment represents independent specimens, not three repeated indentations treated as independent samples.

The designation T6-8h in this paper means solution treatment at 540 °C for 2 h, water quenching, followed by artificial aging at 170 °C for 8 h. The term “highest hardness” refers specifically to the highest mean hardness among the aging durations investigated in this study, not to a universal optimum for the alloy.