



## RESEARCH PAPER

### Experimental characterization of LM13 aluminum piston alloy: composition, mechanical properties, microstructure, and preliminary heat-treatment response

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#### Abstract

LM13 is a near-eutectic Al–Si–Cu–Ni–Mg casting alloy used for pistons and other thermally loaded components. This study provides an integrated preliminary characterization of an industrially relevant LM13 casting by combining optical emission spectrometry, Brinell hardness, tensile and Charpy V-notch testing, optical microscopy, and a duration-based heat-treatment dataset. The measured concentrations of the principal alloying elements were 12.965% Si, 1.468% Cu, 1.044% Mg, and 1.068% Ni, which were within the stated BS 1490 limits used for comparison. The mean as-cast hardness was  $91.7 \pm 2.9$  HBW ( $n = 3$ ). The recorded tensile strength and elongation were 138.63 MPa and 0.72%, respectively, while the Charpy absorbed energy was  $1.3 \pm 1.2$  J ( $n = 3$ ) at 25 °C. In a separate dataset, all ten specimens exhibited increased hardness after heat treatment; the mean increase was 17.2%, and the highest recorded post-treatment hardness was 84 HBW for the specimen associated with 17 h. Optical micrographs showed an aluminum-rich matrix containing constituents that were morphologically consistent with silicon-rich phases and with apparent casting discontinuities. The results establish a consolidated baseline dataset for the LM13 casting under investigation. Because the complete thermal cycle was unavailable and a single specimen represented each treatment duration, the duration-dependent response is interpreted as preliminary. It does not establish an optimal heat-treatment condition

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## 1. Introduction

Aluminum–silicon casting alloys are widely used in automotive and general-engineering components because of their castability, corrosion resistance, and favorable strength-to-weight ratio. LM13 is a near-eutectic Al–Si–Cu–Ni–Mg alloy developed for pistons and other thermally cycled components. Copper and magnesium enable precipitation strengthening, while nickel-containing intermetallic phases contribute to elevated-temperature stability [1,4,8–13]. Published investigations of Al–Si–Cu–Ni–Mg piston alloys have mainly examined controlled alloy modification, phase evolution, squeeze casting, thermal exposure, or fully specified T6 schedules [8–16]. Fewer studies report an integrated quality assessment of an industrial LM13 casting, including

composition, baseline hardness, tensile response, impact energy, optical microstructure, and preliminary heat-treatment records from the same investigation. This practical evidence gap motivates the present work.

Accordingly, the objectives are: (i) to verify the chemical composition of the investigated LM13 casting against the stated alloy limits; (ii) to determine its as-cast hardness, tensile strength, elongation, and Charpy absorbed energy; (iii) to examine its optical microstructure; and (iv) to evaluate the preliminary hardness changes associated with the recorded treatment durations. The contribution is a consolidated baseline dataset and a critical identification of the experimental controls required for subsequent heat-treatment optimization.

## 2. Literature Review

The response of near-eutectic Al–Si–Cu–Ni–Mg piston alloys is governed by alloy chemistry, solidification route, silicon morphology, intermetallic phases, casting discontinuities, and thermal history. Yang et al. [10] demonstrated that Cu addition changes the evolution of nickel-rich phases, while Zuo et al. [11] related the volume fraction of  $\epsilon$ -Al<sub>3</sub>Ni to elevated-temperature tensile and creep performance. Han et al. [9] showed that rare-earth modification can alter the microstructure and mechanical response of an Al–12Si–4Cu–2Ni–0.8Mg piston alloy. More recent work has further established the importance of Ni content and casting route in controlling strength, ductility, and high-temperature stability [12–14]. Heat-treatment studies consistently show that solution treatment, quenching, aging temperature, and aging duration must be considered together. Zeren [15] reported property changes after a specified solution-and-aging sequence in aluminum piston alloys, and Xiao et al. [8] observed a hardness maximum followed by a reduction with increasing aging time in a related Al–Si–Cu–Mg–Ni alloy. Sui et al. [16] likewise demonstrated microstructural and mechanical changes during controlled solution treatment. These studies show why duration alone is insufficient to define an aging response. They also provide the academic basis for treating the present duration-based dataset as preliminary rather than as proof of peak aging or over-aging.

## 3. Materials and Methods/ Experimental Procedure

### 3.1 Alloy and Casting

The investigated material was LM13 (in-house grade CSA-12), a near-eutectic Al–Si–Cu–Ni–Mg casting alloy. Table 1 summarizes the parent-alloy composition used for comparison, together with the stated BS 1490 limits for LM13.

Table 1: In-house CSA-12 specification and stated BS 1490 limits for LM13 (wt.%).

| Element (wt.%) | Parent Alloy Spec. (CSA-12) | Stated BS 1490 LM13 limit |
|----------------|-----------------------------|---------------------------|
| Si             | 11 – 13                     | 10.0 – 13.0               |
| Mg             | 0.8 – 1.3                   | 0.8 – 1.5                 |
| Cu             | 0.8 – 1.5                   | 0.7 – 1.5                 |
| Ni             | 0.8 – 1.3                   | ≤ 1.5                     |
| Fe             | ≤ 0.8                       | ≤ 1.0                     |
| Ti             | ≤ 0.2                       | ≤ 0.2                     |
| Zn             | ≤ 0.2                       | ≤ 0.5                     |
| Pb             | ≤ 0.05                      | ≤ 0.1                     |
| Sn             | ≤ 0.05                      | ≤ 0.1                     |
| Mn             | ≤ 0.5                       | ≤ 0.5                     |

Table 2 summarizes the experimental test matrix used to evaluate the LM13 casting under different characterization conditions. It specifies the material state, sample count, and measured responses for chemical composition, hardness, heat treatment, tensile strength, impact resistance, and optical microscopy, thereby defining the scope of the experimental assessment.

Table 2: Experimental test matrix for the investigated LM13 casting.

| Dataset                | Material condition         | Sample size                | Reported response          |
|------------------------|----------------------------|----------------------------|----------------------------|
| Chemical composition   | As-cast                    | One analyzed sample/report | Elemental composition      |
| Baseline hardness      | As-cast                    | n = 3                      | Brinell hardness           |
| Heat-treatment dataset | Before and after treatment | n = 1 per duration         | Brinell hardness           |
| Tensile test           | As-cast                    | One reported result        | UTS and elongation         |
| Charpy V-notch test    | As-cast                    | n = 3                      | Absorbed energy            |
| Optical microscopy     | As-cast                    | One reported section       | Qualitative microstructure |

### 3.2 Chemical Composition Analysis

The chemical composition of the as-cast sample was determined by OES at Bhartiya Enterprises Material Testing Laboratory, Faridabad, an NABL-accredited laboratory (Test Report No. 31309, dated 8 October 2025) [7]. The measured values were compared with the limits listed in Table 1.

### 3.3 Brinell Hardness Testing

Brinell hardness was measured on three as-cast samples in accordance with ASTM E10-18 [2]. The results are presented in Section 4.2.

### 3.4 Heat Treatment Study

Ten specimens were treated for 15, 16, 17, 18, 19, 20, 21, 22, 23, and 72 h, and hardness was measured before and after treatment. The available test record did not specify the solution-treatment temperature, ageing temperature, quenching medium, or transfer delay. Consequently, this dataset is evaluated only as a preliminary duration-based comparison and is not used to define a complete or reproducible heat-treatment schedule.

### 3.5 Tensile and Impact Testing

Flat tensile specimens were prepared using the geometry shown in Fig. 1 and tested in accordance with IS 1608 (Part 1) [5] (cf. ASTM E8/E8M-16a [3]) at the accredited laboratory (Report Ref. No. 30976, dated 6 October 2025) [7]. Charpy V-notch tests were conducted in accordance with IS 1757 (Part 1):2020 [6] using 10 × 10 × 55 mm specimens with a 2.00 mm-deep V-notch at 25 °C (Report Ref. No. 30978, dated 6 October 2025) [7].

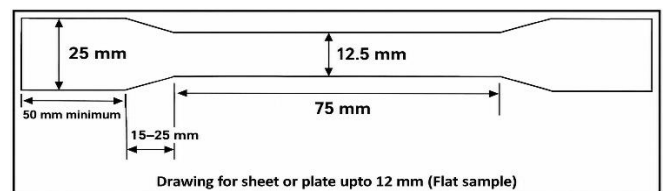


Figure 1: Geometry of the flat tensile specimen used in the study.

### 3.6 Microstructural Examination

A section of the casting was ground, polished, etched with an HF-based etchant, and examined optically at 100× and 500× magnification, following standard metallographic practice. Testing was conducted at the same accredited laboratory (Report Ref. No. 30977, dated 8 October 2025) [7].

## 4. Results and Discussion

### 4.1 Chemical Composition

Table 3 presents the measured elemental composition of the as-cast LM13 sample and evaluates each constituent against the stated BS 1490 requirements. Silicon, magnesium, copper, nickel, iron, titanium, zinc, lead, tin, and manganese remain within the specified limits, while chromium and aluminum are reported without stated limits in the provided comparison. The measured elemental concentrations were within the stated BS 1490 limits listed in Table 1. Silicon content was 12.965%, confirming the alloy's near-eutectic character. Copper, magnesium, and nickel were also present at appreciable levels and are relevant to the precipitation and elevated-temperature response of this alloy system. Because OES represents a local compositional measurement, the present results confirm the analyzed location but do not independently establish compositional uniformity throughout the casting.

Table 3: Measured chemical composition of the as-cast LM13 sample.

| Element | Assessment against the stated BS 1490 limit        |
|---------|----------------------------------------------------|
| Si      | Within limit                                       |
| Mg      | Within limit                                       |
| Cu      | Within limit                                       |
| Ni      | Within limit                                       |
| Fe      | Within limit                                       |
| Ti      | Within limit                                       |
| Zn      | Within limit                                       |
| Pb      | Within limit                                       |
| Sn      | Within limit                                       |
| Mn      | Within limit                                       |
| Cr      | No stated BS 1490 limit (not specified in Table 1) |
| Al      | Balance (remainder; no stated limit)               |

### 4.2 As-Cast Brinell Hardness

Table 4: Brinell hardness of the as-cast LM13 samples.

| Sample No. | Brinell hardness (HBW) |
|------------|------------------------|
| 1          | 94.98                  |
| 2          | 90.00                  |
| 3          | 90.00                  |
| Average    | 91.66                  |

Table 4 summarizes the Brinell hardness measurements obtained from three as-cast LM13 samples. The individual hardness values range from 90.00 to 94.98 HBW, with an average value of 91.66 HBW, providing a representative measure of the baseline hardness of the investigated alloy in its as-cast condition. The three as-cast samples yielded a mean

hardness of 91.7 HBW, a standard deviation of 2.9 HBW, and a range of 90.0–95.0 HBW ( $n = 3$ ). The limited scatter indicates similar hardness at the sampled locations, but it does not demonstrate uniformity throughout the casting. ASTM E10 also cautions that a local indentation may not represent the whole component. The substantially lower initial values in the separate heat-treatment dataset (68–76 HBW), therefore, require reconciliation through batch, sampling-location, and test-condition records. Fig. 2 compares the Brinell hardness values measured for three as-cast LM13 samples. Sample 1 exhibits the highest hardness of 94.98 HBW, while Samples 2 and 3 each record 90.00 HBW. The dashed reference line represents the calculated mean hardness of 91.66 HBW across all three measurements.

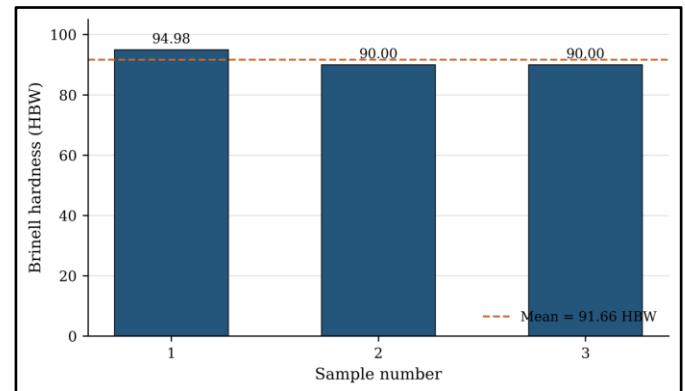


Figure 2: Brinell hardness of the three as-cast LM13 samples; the dashed line indicates the mean value.

### 4.3 Preliminary Heat-Treatment Response

Table 5 compares the hardness of LM13 samples before and after heat treatment for different durations. The results show an increase in hardness after treatment, with improvements ranging from 7.9% to 23.5%. The data indicate that heat treatment enhances hardness, although the magnitude of the improvement varies among the samples investigated. All ten specimens showed a higher post-treatment hardness, with individual increases of 7.9–23.5% and a mean increase of 17.2%.

Table 5: Hardness before and after heat treatment for durations of 15–72 h.

| Sample | Duration (h) | Hardness before treatment (HBW) | Hardness after treatment (HBW) | Increase (%) |
|--------|--------------|---------------------------------|--------------------------------|--------------|
| 1      | 15           | 72                              | 82                             | 13.9         |
| 2      | 16           | 76                              | 82                             | 7.9          |
| 3      | 17           | 68                              | 84                             | 23.5         |
| 4      | 18           | 68                              | 81                             | 19.1         |
| 5      | 19           | 68                              | 81                             | 19.1         |
| 6      | 20           | 68                              | 83                             | 22.1         |
| 7      | 21           | 68                              | 82                             | 20.6         |
| 8      | 22           | 68                              | 75                             | 10.3         |
| 9      | 23           | 68                              | 81                             | 19.1         |
| 10     | 72           | 68                              | 79                             | 16.2         |

The highest recorded value was 84 HBW for the specimen associated with 17 h. Controlled studies of comparable piston alloys show that hardness depends jointly on solution treatment, quenching, ageing temperature, and duration [8,15,16]. In the present dataset, each duration was represented by a single specimen; initial hardness ranged from 68 to 76 HBW, and the complete thermal cycle was unavailable. The fluctuations at 22 and 72 h, therefore, cannot be conclusively attributed to over-ageing, and 17 h should be treated only as a candidate condition for replication. Treatment durations in Figs. 3 and 4 are plotted as discrete experimental categories; their equal spacing in the graph does not represent equal time intervals.

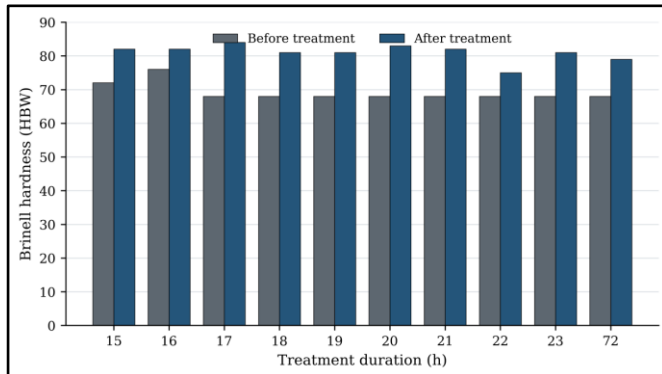


Figure 3: Hardness before and after treatment for the individual specimens associated with each treatment duration. Treatment durations are shown as discrete experimental categories; equal spacing does not represent equal time intervals.

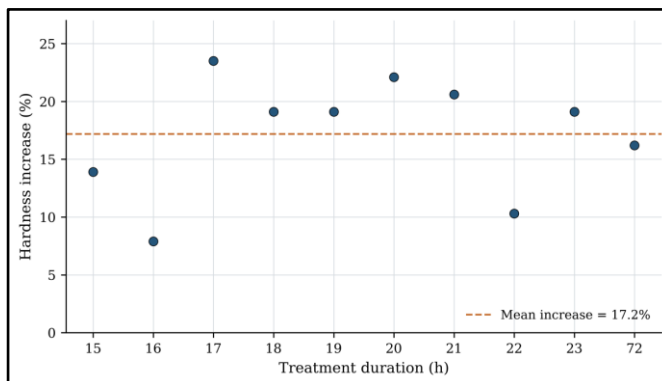


Figure 4: Percentage increase in hardness for the individual heat-treated specimens; the dashed line indicates the mean increase. Treatment durations are shown as discrete experimental categories; equal spacing does not represent equal time intervals.

Fig. 4 illustrates the percentage increase in hardness obtained for the individual heat-treated specimens at different treatment durations. The hardness improvement varies considerably with treatment time, ranging from approximately 8.0% to 23.5%, indicating that the heat-treatment duration has a pronounced influence on the hardness response. The maximum hardness increase of about 23.5% is observed at 17 h, followed by approximately 22.0% at 20 h, while the increases at 18, 19, 21, and 23 h remain in the range of about 19–21%. In contrast, relatively lower improvements are observed at 16 h ( $\approx 8\%$ ), 22

h ( $\approx 10\%$ ), 15 h ( $\approx 14\%$ ), and 72 h ( $\approx 16\%$ ). The dashed horizontal line represents the overall mean hardness increase of 17.2%, showing that most intermediate-duration treatments produce hardness improvements above the average, whereas the 16 and 22 h conditions fall substantially below it. The non-monotonic variation suggests that hardness evolution is governed by competing microstructural mechanisms during heat treatment, such as precipitation, phase transformation, dissolution, and coarsening. Importantly, the treatment durations are plotted as discrete experimental categories, so the equal visual spacing between points should not be interpreted as representing equal intervals of actual treatment time.

#### 4.4 Microstructure

Optical examination revealed an aluminum-rich matrix containing a network of constituents that are morphologically consistent with silicon-rich phases, discrete particles, and apparent casting discontinuities (Fig. 5). Comparable piston-alloy studies identify complex Si-, Cu-, and Ni-bearing phases using SEM-EDS and complementary analyses [9–14]. Figure 5 presents the optical microstructure of HF-etched LM13 alloy at two different magnifications. At 100 $\times$  magnification (Fig. 5a), the micrograph reveals a predominantly  $\alpha$ -Al matrix surrounded by a finely distributed Si-eutectic phase, producing a characteristic dendritic/interdendritic morphology. The higher-magnification image at 500 $\times$  (Fig. 5b) provides clearer details of the primary  $\alpha$ -Al regions and the interdendritic Al-Si eutectic constituent, which appears as relatively darker, irregularly distributed features within the lighter aluminium matrix. The microstructural contrast produced by HF etching facilitates clear differentiation between the aluminium-rich primary phase and the eutectic regions, demonstrating the heterogeneous cast microstructure of LM13.

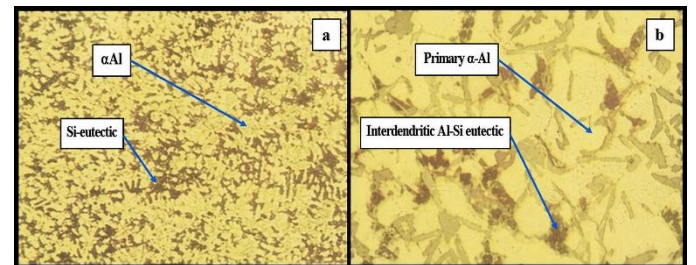


Figure 5: Optical micrographs of HF-etched LM13: (a) 100 $\times$  and (b) 500 $\times$ .

The observed discontinuities and relatively coarse constituents may have contributed to the low elongation and absorbed impact energy. Nevertheless, a direct fracture mechanism cannot be established without quantitative porosity measurements and fractographic examination.

#### 4.5 Tensile Properties

Table 6 presents the tensile test results for the as-cast LM13 alloy. The measured ultimate tensile strength is 138.63 MPa, accompanied by an elongation of 0.72% over a 50 mm gauge

length. These values characterize the alloy's baseline tensile performance and ductility under the reported testing conditions. The single reported tensile result yielded a strength of 138.63 MPa and an elongation of 0.72%; the yield strength was not recorded. These values indicate low ductility in the tested as-cast specimen, but direct numerical comparison with heat-treated or squeeze-cast literature values would be misleading because casting route, temper, and specimen geometry differ [13–16]. The relatively low elongation is qualitatively compatible with coarse constituents and apparent discontinuities, although this mechanism requires replicate testing and fractographic confirmation.

Table 6: Tensile test results for as-cast LM13.

| Parameter                           | Observation |
|-------------------------------------|-------------|
| Tensile strength (MPa)              | 138.63      |
| Elongation (%) (Gauge Length 50 mm) | 0.72        |

#### 4.6 Charpy Impact Toughness

Table 7 summarizes the Charpy V-notch impact response of as-cast LM13 specimens tested at 25 °C. Using  $10 \times 10 \times 55$  mm specimens with a 2.00 mm V-notch, the absorbed energies were 2, 0, and 2 J for the three samples, yielding a mean absorbed energy of 1.33 J. The three specimens absorbed 2, 0, and 2 J, giving  $1.3 \pm 1.2$  J (sample standard deviation;  $n = 3$ ). The small sample size and whole-joule readings limit statistical interpretation. The zero reading may reflect local material variation, notch sensitivity, or instrument resolution; its cause cannot be established without fracture-surface examination and internal-defect assessment.

Table 7: Charpy V-notch impact-test results for as-cast LM13 at 25°C

|                                   |                          |
|-----------------------------------|--------------------------|
| Specimen size (mm)                | $10 \times 10 \times 55$ |
| Notch type/depth                  | V-notch, 2.00 mm         |
| Sample 1 – Absorbed Energy (J)    | 2                        |
| Sample 2 – Absorbed Energy (J)    | 0                        |
| Sample 3 – Absorbed Energy (J)    | 2                        |
| Mean absorbed energy at 25 °C (J) | 1.33                     |

## 5. Conclusions

- The measured chemical composition of the investigated LM13 casting was within the stated BS 1490 limits listed in this study.
- The mean as-cast Brinell hardness was 91.66 HBW, based on three measurements ranging from 90.00 to 94.98 HBW.
- In the separate duration-based heat-treatment dataset, hardness increased by an average of 17.2%, with the highest recorded value of 84 HBW after 17 h. Missing thermal-cycle details, single specimens at each duration, and differing initial hardness values prevent identification of a definitive peak-aging condition.
- Optical microscopy revealed an aluminum-rich matrix with silicon-rich constituents and visible casting discontinuities. Definitive phase identification and quantitative morphology assessment require SEM–EDS or complementary analysis.

- The recorded tensile strength and elongation were 138.63 MPa and 0.72%, respectively. Charpy absorbed energies of 2, 0, and 2 J gave a mean of 1.33 J at 25 °C.
- Future work should document and control the complete solution-treatment, quenching, and aging cycle; use replicate specimens; reconcile the two initial-hardness datasets; and quantify porosity and silicon morphology. Tensile and impact testing should then be repeated for the candidate 17 h condition and compared with the as-cast state. The present dataset provides a preliminary quality-assessment baseline; a substantially expanded factorial dataset would be required before statistically validated regression, or machine-learning modeling could support intelligent heat-treatment control.

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