Journal of Materials and Environmental Science
ISSN : 2028-2508
e-ISSN : 2737-890X
CODEN : JMESCN
Copyright © 2025,
University of Mohammed Premier
Oujda Morocco

J. Mater. Environ. Sci., 2025, Volume 16, Issue 1, Page 56-67

http://www.jmaterenvironsci.com

Enhancing Impact Strength and Hardness of Architectural Aluminum Scrap through Cryogenic Treatment

Birendra Singh Karki [1*], Dr. Anadi Misra [2]**
[1]*Department of Mechanical Engineering, Ph.D. Scholar, G.B.P.U.A.T., Pantnagar, India*
[2]*Department of Mechanical Engineering, Professor, G.B.P.U.A.T., Pantnagar, India*

**Corresponding author, Email address: bskarki57@gmail.com*

***Received** 08 Nov 2024,*
***Revised** 09 Jan 2025,*
***Accepted** 10 Jan 2025*

Keywords:
- ✓ *Deep Cryogenic treatment;*
- ✓ *scrap aluminum alloy;*
- ✓ *Izod impact test;*
- ✓ *Rockwell hardness test;*
- ✓ *Grain Structure;*

***Citation**: Karki B.S., Misra A. (2025) Enhancing Impact Strength and Hardness of Architectural Aluminum Scrap through Cryogenic Treatment, J. Mater. Environ. Sci., 16(1), 56-67*

Abstract: This study investigates the effects of Deep Cryogenic Treatment (DCT) on the mechanical and microstructural properties of aluminium alloys derived from architectural scrap. The alloy composed of Al, Cu, Mg and Si, was melted, alloyed, cast and subjected to treatment with liquid nitrogen at -196°C for 96 hours. DCT resulted in a 4.96% increase in impact strength and an 18.5% improvement in hardness, attributed to significant grain refinement and reduced defects such as voids and micro-cracks. Microstructural analysis revealed a 43.75% reduction in average grain size (from 32 µm to 18 µm) and a 52.89% decrease in standard deviation, indicating a finer, more uniform grain structure. Mechanisms such as dislocation rearrangement, stress relief, and grain boundary pinning contributed to these improvements, enhancing strength and reliability through the Hall-Petch effect. These enhancements render the material more impact-resistant and suitable for high-performance applications. The findings establish DCT as a sustainable method for recycling and improving scrap aluminium alloys, offering significant potential for architectural and industrial applications requiring high strength, durability, and energy absorption.

1. Introduction

Aluminum alloys have some exclusive properties such as lightness, resistance to corrosion, and favorable mechanical property in architecture which has become material of critical necessity for use in this field. Due to the significantly expanded applications in construction, facade systems, and structural components, aluminum alloys have been branded as critical materials in modern architectural design (Al-Alimi *et al.*, 2024). The high interest in recycling scrap aluminum from the architectural sector has been gained over the past few years, mainly due to increased concerns about sustainability and environmental responsibility. The aluminum recycling process has substantial environmental benefits. Because it is considerably more energy-intensive to produce primary aluminum, aluminum recycling saves much more in energy consumption. The process takes only about 5% of the energy that is used to reduce the ore, which explains its high efficiency and sustainability (Raabe, 2003). It is also worth mentioning that the related metallic scrap is of high interest in cementitious materials doping in construction realm (Oulkhir *et al.*, 2024) in the global context of waste management and reduction (Nadir *et al.* 2024).

However, recycled aluminum typically possesses inferior mechanical properties than those of primary aluminum, though the environmental benefits. The losses are due to the accumulation of impurities and degradation in microstructure that occur during multiple melting and processing cycles. Hence, there is a need to develop innovative concepts of alloying and superior methodologies for processing recycled aluminum alloys to regain and improve the alloy's mechanical properties (Mahfoud *et al.*, 2010; Altharan *et al.*, 2024).

The addition of alloying elements, particularly Cu, Mg, and Si, was used as one of the promising approaches for increasing the strength, hardness, and toughness properties of recycled aluminum alloys. The addition helps in precipitation hardening, intermetallic compound formation, and modification of the microstructure, with consequent increases in mechanical properties. For instance, by adding Cu and Mg into the Al-Si alloys, the strength of the alloy as well as the wear resistance had improved upon the strengthening capability of these materials for high temperature applications requiring stability and mechanical reliability (Achitei *et al.*, 2023; Vaudreuil *et al.*, 2022). Even tiny concentrations of alloying elements, such as Cu with 0.05 wt% and Zn with 0.06 wt%, may significantly influence the two factors of thermal stability and mechanical properties of precipitate crystal structures in Al-Mg-Si alloys. Furthermore, from a practical standpoint, these alloys are known by the ability to be manufactured by number of fabrication processes such as casting, machining and additive manufacturing (El Jai *et al.* 2021, Igwe *et al.* 2024).

Also, in addition to the classical post-processing treatments advanced post-processing techniques have emerged over the recent years with cryogenic treatment, now opening up avenues to improvement in the mechanical properties of aluminum alloys. Exposure of metals to the ultra-low temperatures referred to as cryogenic treatment, and more specifically, deep cryogenic treatment (DCT), involves exposure of metals to temperatures around -196°C in liquid nitrogen. Induction would lead to beneficial microstructural changes such as grain refinement, secondary precipitation, and a reduction in residual stresses, and these taken together would improve material performance. There have been studies to indicate the hardness, impact strength, and wear resistance of aluminum alloys have been significantly enhanced by the cryogenic treatment, mainly in cases where such alloys contain alloying elements like Cu, Mg, and Si (Jovicevic-Klug *et al.*, 2020), (Li *et al.*, 2015). For Al-Mg-Si alloys, DCT allows for the reformulation and rejuvenation of dispersoids in natural aging with cuboidal-dispersoid morphology transformed to spherical shapes and increased densities, ultimately improving the alloy's hardness over time (Jovicevic-Klug *et al.*, 2020). For the Al-Zn-Mg-Cu alloys, cryogenic treatment initiates phase transformations that strengthen the alloy by forming Guinier-Preston zones and the metastable η′ phase (Li *et al.*, 2015). Nevertheless, the impact of cryogenic treatment is composition dependent on the alloy and specific parameters involved in the cryogenic treatment. For instance, in Al-Cu-Mg-Ag alloys, DCT results in the deformation by plasticity due to high density of dislocations in the α-Al matrix that reduces the size of the Ω precipitates but increases their number density. This enhances the mechanical properties of the alloy (Wang *et al.*, 2023). Additionally, DCT increased the wear resistance of Al-Mg-Si alloys by up to 55% without degrading other critical mechanical properties of the alloy (Jovicevic-Klug *et al.*, 2020).

Critical to achieving maximum benefits from these combined treatments is the optimization of the parameters in the DCT process. Fine-tuning the conditions of treatment leads to significantly improved microstructure, mechanical properties, and corrosion resistance in recycled aluminum alloys as an environmentally friendly yet high-performance alternative for the architectural industry. This study is important for the improvement of recycled aluminum alloys by combining alloying and cryogenic treatment. About the present sustainability requirements and future architectural material development trends, this article could potentially go through exploring the possibility of increasing the mechanical properties of recycled aluminum by alloying it with Cu, Mg, and Si. After the preparation of the alloys, materials went through cryogenic treatment and then tested for performance by Izod impact and Rockwell hardness tests. These results therefore provide a comprehensive understanding of how these technologies contribute to recyclable, more powerful, and more resistant recycled aluminum alloys in line with the goal of sustainable material development in architecture.

2. Material Methodology

2.1 Sourcing and preparation of specimens

The aluminum scrap architectural alloy was derived from pieces cut during the fabrication process. Four kilograms of scrap aluminum was melted and alloyed together with 200 g of copper (Cu), magnesium (Mg), and silicon (Si). Cu, Mg, and Si were selected because of their known strengthening effects in aluminum alloys.

2.2 Casting Procedure

The casting process had a significant effect on the microstructure and the mechanical properties of the aluminum alloy. The base material used for the work involved scrap architectural aluminum alloy from decommissioned structures. The raw alloy used was already in a recycled state that had to go through various operations from preparation to casting before undergoing mechanical testing. The steps involved in the preparation and casting of the alloy include:

2.2.1 Cleaning of Scrap Aluminum

Before melting, the scrap aluminum underwent thorough cleaning to remove impurities and dirt layers mainly associated with recycled materials, along with oxide layers. This was necessary in order to obtain quality in the final alloy and reduce contamination, which would have otherwise adversely affected the material's properties. Cleaning involved mechanical scrubbing and chemical treatment, where the aluminum was soaked in a mild acid solution to dissolve surface contamination. The scrap was washed and dried and then moved to the furnace for melting.

2.2.2 Melting in Coal Furnace

The scrap aluminum then cleaned was put in a coal-fired furnace. While direct-melting using an electric or gas furnace is more common owing to its better control of the melt temperature, the coal furnace has to be used here for it is simply available and used widely in recycling facilities. Though having a high heat capacity, coal furnaces require to be properly handled with well monitored airflow and temperature lest this will result in overheating and excess carbon impurities get injected.

Slag (non-metallic waste) and other impurities that formed at the top of the aluminum melt were removed during the smelting process. The operation guarded against the entry of oxides into the alloy, along with unwanted constituents which might have an effect on the alloy's mechanical properties. Following the melting of the scrap entirely, the aluminum melt was left to be stabilized in temperature before introducing the alloying elements of copper, magnesium, and silicon.

2.2.3 Alloying Elements

After the aluminum had been completely melted, the following alloying elements were added to the molten aluminum: copper (Cu), magnesium (Mg), and silicon (Si). Based on the total weight of scrap aluminum as 4 kg, the exact amount of grams of each alloying element needed was calculated: 200 g each. The three elements added are symbiotic strengtheners of aluminum alloys:

2.2.4 Liquidation Stirring

All the alloying elements were added, and the molten mix was stirred vigorously in order to ensure that the mixing is even. Stirring is very important in casting processes as it prevents the formation of segregated regions where alloying elements might concentrate. Uniform mixing is essential to ensure that the microstructure of the material is uniform throughout, hence ensuring that its mechanical properties are constant throughout. At this stage, there was cautious attention not to allow air entrainment as this may lead to the porosity or gas bubbles in the cast material. There was a hand stirrer use, and in this process, the molten metal was kept at a steady temperature so that it does not solidify early and overheat.

*2.2.5 **Pouring into Molds***

The molten mixture is poured into preheated molds that have an inside temperature of about 150°C to reduce the thermal shock and allow smooth filling of the molten metal. This leads to the development of internal stresses in the alloy, with a resultant tendency to cracking or deformation after castings because of rapid cooling.

The specimen requirements for subsequent mechanical testing drove the design of the casting molds. The molds were properly dimensioned to allow preparation of samples for both Izod impact tests and Rockwell hardness tests, and uniformity could be ensured across all specimens.

2.2.6 **Solidification**

Pouring molten aluminium alloy into the molds allowed cooling of the castings in ambient air. Instead of using other forced cooling techniques, such as water quenching, natural air cooling was used to prevent the induction of thermal stresses that would cause cracks or warping of the cast samples. Ambient air cooling gives a slow cooling rate where the solidification of the aluminum alloy is controlled.

Microstructure develops at solidification; development of microstructure is dependent upon cooling rate and addition of alloying elements. Normally, large grains are favored by cooling rate, while Si and Mg additions are known to refines microstructure by favoring precipitates and secondary phase formation (Callegari *et al.,* 2023).

Prepared cast samples were removed from the molds after complete solidification. They were prepared for the next treatments and tests, including cryogenic treatment, followed by mechanical testing, as described in subsequent sections of this work.

2.3 **Cryogenic Treatment**

Cryogenic treatment is an established process applied to a number of metals, such as aluminum alloys for enhancement in mechanical properties by exposing those to ultra-low temperatures. Cryogenic treatment was thus applied to cast aluminum specimens in order to improve their hardness, toughness, and overall performance (Venkateswarlu *et al.,* 2024). The cryogenic medium here was liquid nitrogen; the cooling, holding, and warming phases of treatment were accurately controlled so that all thermal shock or stress introduced would be avoided. As shown in figure 1, the all treatment processes which are carried out in this paper. After casting the solution treatment is necessary for making homogeneous phase among the entire alloying element followed by age hardening and then finally deep cryogenic treatment.

2.3.1 Purpose of Cryogenic Treatment

Deep cryogenic treatment (DCT), sometimes also called cryogenic treatment, is widely used for structural modification of cast aluminum alloys with a view to attaining improvement in their mechanical properties such as strength, hardness, and impact toughness. At the ultra-low temperatures, close to liquid nitrogen, that is about -196°C, it induces the precipitation of fine secondary phases within the alloy matrix and grain refinement of the alloy. These microstructural changes substantially contribute to realizing improvements in material performance. For instance, grain boundary and secondary phase precipitate refinement increase the deformation resistance of the alloy, thus increasing hardness. The residual stresses in the material also tend to decrease when it is cryogenically treated, which eventually leads to better dimensional stability and improved resistance to fatigue (Gao *et al.*, 2022). Furthermore, the impact toughness and hardness Strength of the alloy are simultaneously improved due to these microstructural changes, and therefore, alloy turns out to be fit for high-performance applications. **Figure** 1, shows the full heat and cryogenic treatment process.

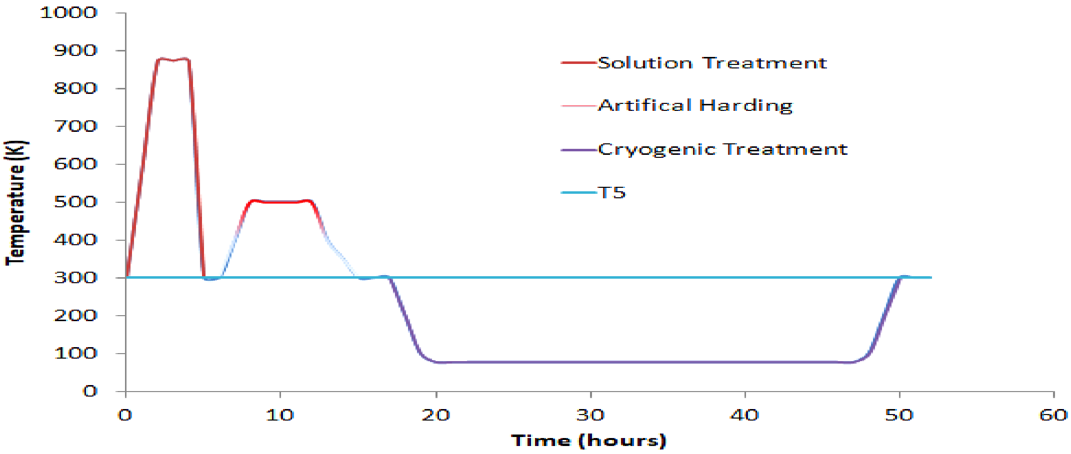

Figure 1. Full Thermal Treatment Process Cycle

In addition to heterogeneous dispersion, cryogenic treatment also promotes homogeneous dispersions of alloying elements such as copper (Cu), magnesium (Mg), and silicon (Si) in the aluminum matrix. The conventional casting process leads to the development of impurities, dislocations, and voids, resulting in uneven mechanical properties of the material. In contrast, the cryogenic process inhibits the introduction of these defects, thus ensuring uniformity in the microstructure. This homogeneous distribution of alloying elements significantly enhances the general properties of the material, like strength and toughness by reinforcing the structural integrity of the cast aluminum alloy. Moreover, cryogenic treatment provides the optimization of the grain structure, which eventually results in improved performance under mechanical stress, allowing the alloy to take harsher conditions.

A very critical factor about the effectiveness of cryogenic treatment is the controlled cooling process. Not only does the treatment cool the alloy to cryogenic temperatures but also holds it for a specified time, followed by slow warming back to room temperature. This process makes careful handling necessary; otherwise it will often induce severe thermal shock that can also lead to stress and cracking in the material. Research studies have shown that if the cooling, holding, and warming processes are properly controlled, there would be a successful upgrading of the desired mechanical properties without structural failure of the alloy. Besides enhancing the properties of aluminum alloys, cryogenic treatment has been applied to many other materials: its versatility. While beneficial effects of cryogenic treatment of steels have been amply documented, research has been extended to other metallic alloys and materials (Rivolta *et al.,* 2022), (Gerosa *et al.,* 2023), (Yao *et al.,* 2023), (Li *et al.,* 2024).

Several studies have demonstrated that cryogenic treatment performed well for various materials such as hard metal, gray cast iron, and Aus-tempered Ductile Iron (ADI) (Solic *et al.,* 2016). The study on combining deep cryogenic treatment with tempering indicated that the former had a positive influence on increasing the matrix microstructure of ADI and enhanced both the abrasion wear resistance and hardness (Solic *et al.,* 2016). Besides, research has been conducted on cryogenic treatment of magnesium-based nano-composites, and scientists discovered enhanced density, raised ignition temperature, compressive yield strength, ductility, and micro hardness (Gupta *et al.,* 2023). While Aluminum alloys were the most considerable recent subjects of the cryogenic treatment research, this new technology also finds its applications in numerous materials. Another emerging material area where cryogenic treatment has the potential to improve material properties is industrial applications as a treatment across multiple materials.

2.3.2 Cryogenic Treatment Setup

a) Cooling Stage

Cast al alloy specimens that cooled to room temperature from solidification via ambient atmosphere have been treated in a cryogenic chamber. The cryogenic medium selected was liquid nitrogen that boils at -196°C. Thermal shock that may cause cracking or excessive internal stresses from the cooling rate was avoided with careful selection (Edeskuty *et al.,* 1996). Cooling of the specimens from room temperature to -196°C was permitted over several hours. The process occurred gradually and ensured even distribution of thermal gradients in the specimens, thus being non-conducive to the localization of stress formation. It gave a stable and constant low-temperature environment. Cooling rates and temperature were closely monitored with the help of thermocouples attached to the specimens, and assured that the desired cooling curve was followed.

b) Holding Phase

Once these samples reached the desired temperature of -196°C, they were kept at the temperature for a long time of 96 hours. The holding time is an important factor for the full effects of cryogenic treatment to come through. This long period at very low temperatures allows the following microstructural changes:

Precipitation Hardening: Cryogenic treatment helps enhance the formation and precipitation of fine secondary phases such as aluminium-copper and aluminium-silicon intermetallic compounds (Moroff *et al.,* 2011).. These precipitates act as barriers to the dislocation movement, so increasing the hardness of strength in the alloy. Austenite Retained Reduction: Cryogenic treatment in alloys such as steel reduces retained austenite. In aluminum, the above phase transformation does not occur. The above potential of reduction of an internal stress is still valid; however, it will occur due to the stabilization of a phase. Cryogenic treatment in aluminum alloys refines the grain structure and decreases micro-cracks or voids that might have occurred during the solidification process.

Stresses Relief: The low temperatures relieve residual stresses that may have been introduced during casting and solidification. Relaxation of these stresses increases the toughness in the material and enhances the impact resistance as depicted by subsequent Izod impact tests.

c) Reheating Process

After the 96-hour hold at -196°C, the specimens were slowly warmed back up to room temperature. The warming step is as important as the cooling step because rapid warming can cause thermal shock or uneven expansion, leading to cracking or warping of the material. Thus, the specimens came up to room temperature over several hours so that the material may equilibrate without introducing new stresses.

2.3.3 Aluminium Alloys Benefits of Cryogenic Treatment

Several of the mechanical properties were improved in the cryogenic treatment.

Improved Hardness: Indicated from the test results on Rockwell hardness, the specimens cryogenically treated show improvement in the values. Such an improvement can be attributed to the refinement of the microstructure and the distribution of finely distributed precipitates that restrain the movement of dislocation. Increased Impact Toughness Izod impact test data gave a clear evidence that the processing the specimens were noticeably increased energy absorbing capability. Such a result would denote that there is greater resistance to fracture for the impact type of load, as caused by reduction in size of internal defects and the refinement of grain structures.

3. Experiments

3.1 Izod Impact Test

The Izod impact test determines the toughness of a material and the capability of the material to absorb energy at fracture time. The test specimens are solution-treated at 500°C with an aging period of 5 hours under T6 temper conditions before carrying out the Izod impact test.

Impact tests are commonly used to study a material's toughness, which is determined by its ability to absorb energy during plastic deformation. Brittle materials exhibit low toughness due to their limited capacity for plastic deformation. The impact value of a material can also varies with temperature, typically decreasing at lower temperatures as the material becomes more brittle (**Figure 1**). In Izod testing, higher speeds and impact energies can be achieved using vertical pendulum setups, providing reliable and qualitative collision data. Impact testing standards include ISO 178 and ASTM D6110 for Izod testing. For calculation, we use the formula:

$$Impact\ Strength = \frac{Impact\ Energy}{Cross-section\ Area}\ (\mathrm{kJ/m^2})\ \ \text{- (i)}$$

3.2 Rockwell Hardness Test

The Rockwell hardness test is an extensively used methodology for checking the hardness of materials that includes alloys. It measures the hardness by pressing an indenter, diamond cone or hardened steel ball, onto the surface of a specimen with a certain load. The hardness is calculated by measuring the depth of the indentation left there. This process is standardized under ASTM E-18 and finds favor for its accuracy and ease of use (**Figure 3**).

This procedure, though in the simple outline, could be more challenging to apply due to various properties of the tested metal samples. As a matter of fact, different materials vary in size, shape, and homogeneity. This makes one method hardly applicable to all tests. For this purpose, the Rockwell test comprises 30 scales, all of which consist of exclusive combinations of indenter types and load forces. In selecting the appropriate scale, observers have to consider such factors as the character of the material and restrictions of a given scale.

Figure 2. Izod Testing Setup

Figure 3. Rockwell Hardness Test Setup

4. Results and Discussion

4.1 Izod Impact Results

Given: Cross-sectional Area = 80×10−6 m^2

For each treatment condition, minimum three samples were tested and all the energy values are recorded from digital output screen. These findings and calculated impact strength form **equation (i)** is listed in **Table 1**and **2** for Impact test. For hardness test result from digital Rockwell hardness test are listed in **Table 3** and **4.**

Table 1. Experimental Impact Test Result without DCT

Specimen without DCT	Energy (J)	Impact strength (kJ/m^2)
S1	0.4525	5.65625kJ/m^2
S2	0.4527	5.65875kJ/m^2
S3	0.4523	5.65375 kJ/m^2
Average	0.4526	5.6575kJ/m^2

Table 2. Experimental Impact Test Result with DCT

Specimen with DCT	Energy (J)	Impact strength (kJ/m^2)
S1	0.47491	5.936375kJ/m^2
S2	0.4750	5.9375kJ/m^2
S3	0.4752	5.9400kJ/m^2
Average	0.47503	5.9379kJ/m2

The provided data consists of impact energies and corresponding impact strengths for specimens both without and with DCT (Deep Cryogenic Treatment). Below is a summary of the results:

- Average Impact Strength without DCT: 5.6575 kJ/m^2
- Average Impact Strength with DCT: 5.9379 kJ/m^2
- Percentage increase in impact strength due to DCT: 4.96%

Table 3. Experimental Hardness Test Result without DCT

surface	**Hardness Scale**					**average**	**Standard deviation**
	1	2	3	4	5		
Bottom	101	102	98	100	105.6	101.32	2.51587
Top	104	99	101	103	102	101.8	1.720465

Table 4. Experimental Hardness Test Result with DCT

surface	Hardness Scale					Avg.	Standard deviation
	1	2	3	4	5		
Bottom	117	122	118	120	123	120	2.28
Top	124	119	121	118	122	120.8	2.387

The provided data consists of impact energies and corresponding impact strengths for specimens both without and with DCT (Deep Cryogenic Treatment). Below is a summary of the results:

- Bottom Surface: The hardness increased by approximately 18.44% after DCT.
- Top Surface: The hardness increased by approximately 18.66% after DCT.

These calculations show a consistent increase in hardness of around 18.5% for both the top and bottom surfaces as a result of DCT.

4.2 Microstructural Analysis

Microstructural examination has been done, and it is clear that the cryogenically treated sample undergoes the formation of refined grains and better alloying elements distribution. Grain size is highly reduced, and the secondary precipitates are uniform. Improved hardness and toughness of treated samples have been related to a finer microstructure. Nucleation of fine precipitates significantly increased with Cu, Mg, and Si deposition because they facilitated higher homogenization in microstructure. The cryogenic treatment also minimized the defects such as voids and micro-cracks, often seen in the cast scrap aluminum alloys. Improvement in mechanical properties, like hardness and impact strength, was supported by changes observed at the microstructural level through optical microscopy 100X magnification (as shown in **figure 4**). Average grain size (µm) and standard deviation is given in **Table 5.**

The microstructural changes observed in the aluminum alloy at 100X magnification (**Figure 4**) highlight the significant impact of DCT on grain morphology and uniformity.

a) Grain Morphology Before DCT (Figure 4a):
   - ➢ The microstructure prior to DCT exhibits coarse and irregularly shaped grains.
   - ➢ The boundaries are prominent, suggesting larger grain sizes averaging 32 µm (as per Table 5).
   - ➢ The high standard deviation **(**24.2 µm**)** indicates a wide variation in grain sizes, with clusters of unevenly distributed grains dominating the microstructure.

b) Grain Morphology After DCT (Figure 4b):

- Post-DCT, the grains become noticeably smaller and more uniform. The average grain size reduces to 18 µm, accompanied by a lower standard deviation **(**11.4 µm), as reported in **Table 5**.
- The refinement of grain boundaries is evident in the image, with more consistent and evenly distributed grains compared to the untreated condition.

c) Visual Confirmation of Grain Refinement:

- The comparison of **Figure 4a** and **Figure 4b** clearly illustrates the reduction in grain size and improvement in uniformity. The boundaries in the DCT-treated sample (**Figure 4b**) appear sharper and more compact, indicating a finer and more homogeneous microstructure.

d) Mechanisms Leading to Grain Refinement:

- The DCT process likely facilitates the rearrangement of dislocations and the annihilation of residual stresses, promoting nucleation sites for smaller grains.
- The more uniform distribution observed after DCT aligns with the thermal cycling effect, which refines the microstructure through stress relief and grain boundary pinning mechanisms.

e) Implications for Mechanical Properties:

- The reduction in average grain size enhances the alloy's strength and hardness, as finer grains impede dislocation motion (Hall-Petch effect).
- Improved grain uniformity reduces the likelihood of localized weak points, resulting in better mechanical consistency and reliability.

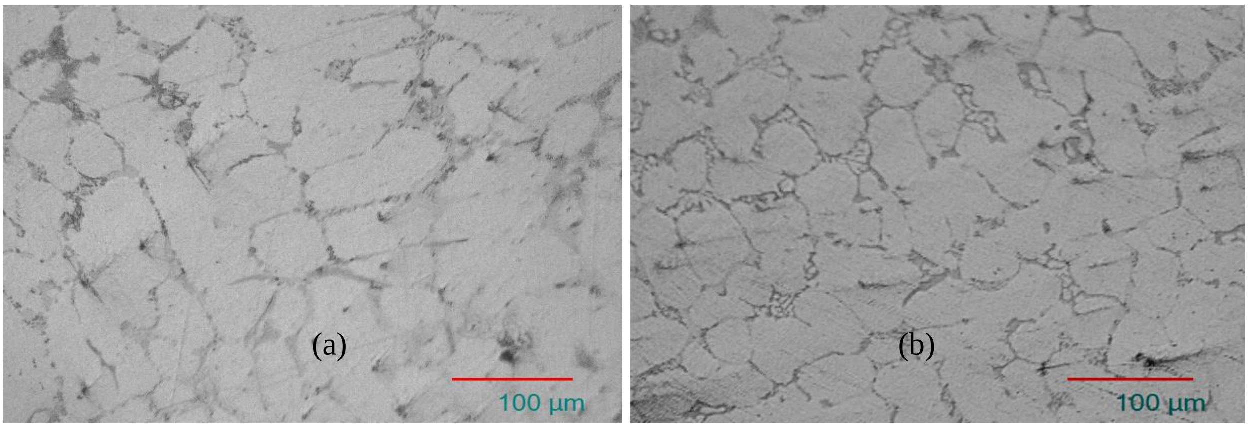

Figure 4. Grain Structures a) Before DCT b) After DCT

Table 5. Microscopic analysis of Grain size

Condition	Before DCT	After DCT
Avg. Particle Size (µm)	32	18
Standard Deviation (SD)	24.2	11.4

Conclusion

This research has demonstrated that Deep Cryogenic Treatment (DCT) at -196˚C for 96 hours significantly improves the mechanical and microstructural properties of aluminum alloys. The treatment resulted in a 4.96% increase in impact strength, reflecting an enhanced ability to absorb energy and resist fracture under sudden loading conditions. Additionally, DCT produced a uniform improvement in hardness, with an average increase of 18.46% on the bottom surface and 18.66% on the top surface compared to untreated specimens, indicating the consistency and reliability of the process. Long-term stability of these improvements was validated through flexural tests conducted after three months, highlighting the durability of DCT's effects in improving mechanical performance.

Microstructural analysis revealed substantial grain refinement following DCT, with the average grain size reduced by 43.75% (from 32 µm to 18 µm) and the standard deviation decreasing by 52.89%, signifying finer and more uniform grains. This microstructural refinement can be attributed to the mechanisms of dislocation rearrangement, stress relief, and grain boundary pinning promoted by DCT. The smaller grain size enhances the material's strength and hardness through the Hall-Petch effect, while improved grain uniformity ensures better mechanical consistency and reduces the likelihood of localized weak points. These findings establish DCT as a reliable and effective method for improving both the mechanical properties and microstructural quality of aluminum alloys, making it a promising technique for industrial applications that require high strength, durability, and reliability.

Disclosure statement: *Conflict of Interest:* The authors declare that there are no conflicts of interest.
Compliance with Ethical Standards: This article does not contain any studies involving human or animal subjects.

References

Achitei, D., Vizureanu, P., Minciună, M. G., Al Bakri Abdullah, M. M., & Sandu, I. G. (2015). Study on Al-Si alloys Properties Enhancement. *Applied Mechanics and Materials*, 754, 634-638.

Al-Alimi S., Yusuf N. K., Ghaleb A. M., et al. (2024), Recycling aluminium for sustainable development: A review of different processing technologies in green manufacturing, *Results in Engineering*, 23, 102566, ISSN 2590-1230, https://doi.org/10.1016/j.rineng.2024.102566

Altharan, Y. M., Shamsudin, S., Al-Alimi S., Saif Y., Zhou W. (2024), A review on solid-state recycling of aluminum machining chips and their morphology effect on recycled part quality, *Heliyon*, 10(14), e34433, https://doi.org/10.1016/j.heliyon.2024.e34433

Callegari, B., Lima, T. N., & Coelho, R. S. (2023). The influence of alloying elements on the microstructure and properties of Al-Si-based casting alloys: a review. *Metals*, 13(7), 1174.

Edeskuty, F. J., & Stewart, W. F. (1996). Safety in the handling of cryogenic fluids. *Springer Science & Business Media*, 19-23.

Gao, Q., Jiang, X., Sun, H., Fang, Y., Mo, D., Li, X., & Shu, R. (2022). Effect mechanism of cryogenic treatment on ferroalloy and nonferrous alloy and their weldments: A review. *Materials Today Communications*, 33, 104830.

Gerosa, R., Panzeri, D., Rivolta, B., & Casaroli, A. (2023). Deep cryogenic treatment of AA7050: tensile response and corrosion susceptibility. *Discover Materials*, 3(1), 2.

Gupta, S., Parande, G., Tun, K. S., Gupta, M. (2023). Enhancing the Physical, Thermal, and Mechanical Responses of a Mg/2wt.% CeO_2 Nanocomposite Using Deep Cryogenic Treatment. *Metals*, 13(4), 660.

Igwe, N.C., Akhrif, I., El Jai, M. et al. An experimental investigation of the influence of SLM input factors on the as-built AlSi10Mg surface quality. Int J Adv Manuf Technol 136, 619–674 (2025). https://doi.org/10.1007/s00170-024-14657-7

Jovicevic-Klug, P., & Podgornik, B. (2020). Review on the effect of deep cryogenic treatment of metallic materials in automotive applications. *Metals*, 10(4), 434.

Li, G., Cao, Z., Wang, H. et al. (2024). Effect of deep cryogenic treatment on microstructures and mechanical properties of automotive 6063Al alloy. *J Mater Sci* 59, 5558–5575, https://doi.org/10.1007/s10853-024-09505-8

Li, C. M., Cheng, N. P., Chen, Z. Q., Guo, N., & Zeng, S. M. (2015). Deep-cryogenic-treatment-induced phase transformation in the Al-Zn-Mg-Cu alloy. *International Journal of Minerals, Metallurgy, and Materials*, 22, 68-77.

Mahfoud, M., & Emadi, D. (2010). Aluminum recycling-challenges and opportunities. *Advanced Materials Research*, 83, 571-578.

Moroff, G., AuBuchon, J. P., Pickard, C., Whitley, P. H., Heaton, W. A., & Holme, S. (2011). Evaluation of the properties of components prepared and stored after holding of whole blood units for 8 and 24 hours at ambient temperature. *Transfusion*, 51, 7S-14S.

Oulkhir, F., Akhrif, I. & El Jai, M. (2025). 3D concrete printing success: an exhaustive diagnosis and failure modes analysis. Prog Addit Manuf 10, 517–559. https://doi.org/10.1007/s40964-024-00638-5

Raabe, D. (2023). The materials science behind sustainable metals and alloys. *Chemical reviews*, 123(5), 2436-2608.

Rihani, N., Akhrif, I., El Jai, M. (2024). Proposition and design of a new Micro-Architected Domes family: A biomimicry-based approach,Frontiers of Architectural Research, Volume 13, Issue 3, pp. 650-667. https://doi.org/10.1016/j.foar.2024.01.004

Rivolta, B., Gerosa, R., & Panzeri, D. (2022). Cryogenic treatment of 7050 Aluminum Alloy to improve corrosion resistance. https://doi.org/10.21203/rs.3.rs-1369733/v1

Solic, S., Godec, M., Schauperl, Z., & Donik, Č. (2016). Improvement in abrasion wear resistance and microstructural changes with deep cryogenic treatment of austempered ductile cast iron (ADI). *Metallurgical and Materials Transactions* A, 47, 5058-5070.

Vaudreuil S., Bencaid S-E., Vanaei H.R., El Magri A. (2022) Effects of Power and Laser Speed on the Mechanical Properties of AlSi7Mg0.6 Manufactured by Laser Powder Bed Fusion. *Materials.* 15(23), 8640. https://doi.org/10.3390/ma15238640

Venkateswarlu, K., Varma, K. P. V., & Nutakki, U. K. (2024). Effect of nanoparticle reinforcement and cryogenic treatment on aluminum alloys for enhancement of mechanical and microstructural characteristics-a review. *International Journal on Interactive Design and Manufacturing (IJIDeM)*, 1-20.

Wang, J., Xie, J., Ma, D., Mao, Z., Liang, T., Ying, P., ... & Wang, W. (2023). Effect of deep cryogenic treatment on the microstructure and mechanical properties of Al–Cu–Mg–Ag alloy. *Journal of Materials Research and Technology*, 25, 6880-6885.

Yao E., Zhang H., Ma K., Ai C., Gao Q. (2023), Xiaoping Lin, Effect of deep cryogenic treatment on microstructures and performances of aluminum alloys: a review, *Journal of Materials Research and Technology*, 26, 3661-3675, ISSN 2238-7854, https://doi.org/10.1016/j.jmrt.2023.08.140

(2025) ; http://www.jmaterenvironsci.com