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APPLICATION OF DIRECTIONAL SOLIDIFICATION TECHNOLOGY IN THE CASTING OF ALUMINUM ALLOY FOR ENGINEERING APPLICATIONS

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ABSTRACT
This research investigates the mechanical and microstructural properties of a Directionally Solidified (DS) aluminum alloy produced using a tapered pattern of 500 mm length, with diameters of 40 mm and 20 mm at opposite ends. The study aims to evaluate how varying cooling rates across the casting influence hardness, impact strength, tensile strength, and grain morphology. The methodology involved producing a tapered wooden pattern, preparing the mold, melting and pouring the aluminum alloy, and carrying out shakeout and finishing operations. The solidified alloy was sectioned into specimens from both thin and thick ends for testing. Mechanical characterization included impact and hardness testing, with tensile strength estimated from hardness values. Microstructural examination was conducted using optical microscopy. The results revealed a clear relationship between cooling rate, grain morphology, and mechanical properties. Specimens from the thinner end, which solidified rapidly, developed fine equiaxed grains that enhanced impact resistance (up to 56 J) but exhibited lower hardness and tensile strength. Conversely, specimens from the thicker end solidified more slowly, forming coarse dendritic and columnar grains. These structures yielded higher hardness (up to 40.25 HV) and tensile strength (121 MPa), but reduced toughness (impact energy as low as 45 J).The study concludes that directional solidification effectively tailors the mechanical performance of aluminum alloys by controlling grain structure through cooling gradients. Fine equiaxed grains favor impact resistance, while coarse dendritic grains enhance hardness and strength. The research recommends optimizing DS casting parameters to balance toughness and strength for industrial applications, particularly in aerospace, automotive, and structural components.

Keywords: Directional Solidification, Solid/liquid interface, Characterization, Microstructures

1.0 INTRODUCTION

Recent approach to materials modification is in controlling its solidification method in order to conform to the analogy of applying materials with high strength-to-weight ratio in engineering applications. This approach is referred to as Directional Solidification (DS) which is a a controlled process where molten metal solidifies towards a riser, preventing defects and ensuring high-quality castings for critical applications (Ji*et* al., 2020) with effective control, the possible casting defects that usually ensued from this process can be minimize and eradicated (Kraft and Lippold, 2011; Sigworth, 2016).

However, when casting a large components, effective heat extraction without defects is relatively difficult during power-down as it results in low thermal gradients at the solid/liquid Interface (Gell *et al.*, 1974). This is primary due to the cooling direction by conduction through the casting to the cooled chill plate. As a large casting is withdrawn, this method of heat extraction quickly becomes inefficient due to the low thermal conductivity of most super alloys; radiation through the vacuum becomes the dominant mode of heat extraction, resulting in low thermal gradients at the solidification front.[Kermanpur *et al.*, 2000].

To maintain a stable solid/liquid dendritic interface as gradients fall to low levels, withdrawal rates must be reduced and defects such as freckles and misaligned grains form more frequently, resulting in a high rejection rate of these castings (D'Souza *et al.*, 2000). Reducing the withdrawal rate also extends the process time, increasing mold-metal reaction and mold creep and cracking problems (Fitzgerald and Singer, 1997; Suyitno *et al.*, 2019).

One of the materials subjected to directional solidification is alluminium. This is due to its amenability to heat treatment and alloying. Despite the widespread industrial use of aluminum alloys due to their excellent strength – to – weight ratio and corrosion resistance, their mechanical performance and reliability are significantly influenced by the solidification process. Traditional casting methods often lead to non – uniform grain structures defects such as porosity, which compromise mechanical integrity. DS often offers a promising technique to control grain orientation and improve properties, but the correlation between solidification parameters, microstructure evolution, and mechanical behavior in directionally solidified alloys remains inadequately understood. Therefore, there is a need to systematically investigate how DS affects the microstructural features and mechanical properties of aluminum alloys to optimize their processing and performance in engineering applications. This research therefore focuses on the effects of directional solidification on the mechanical and microstructural property of a sand cast aluminum alloy.

2.0 EXPERIMENTAL PROCEEDURE

As a way of recycling mechanism, aluminium scraps from drink cans were collected from the various environments in Kogi central.

Table 1: Spectrometric analysis of the aluminium

Component	Al	Mg	Si	Fe	Cu	Cr	Zn	Ti	Mn	Others
%tages	96.15	0.81	0.52	0.71	0.22	0.04	0.21	0.1	0.09	Bal.

A single – piece pattern was designed based on the required specimen sizes for impact, hardness tests, allowing for machining allowances. The pattern was made from seasoned hardwood to ensure dimensional stability, and draft angles were incorporated to facilitate removal from the mold. The surface was smoothed and coated with a protective finish to improved mold surface quality.

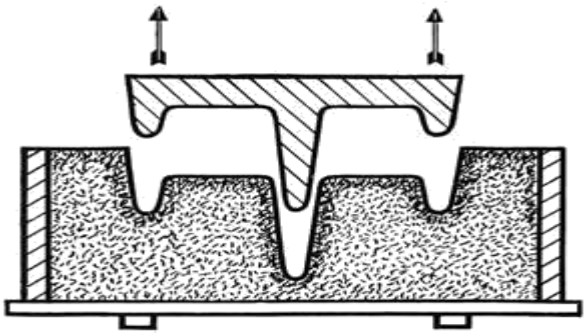


Fig. 1: Tapered Patterns in the drag



Fig. 2: Cleaning and Shakeout

The drag half of the molding box was placed on a flat surface and the pattern positioned centrally. Parting powder was applied over the pattern to prevent sticking. Silica sand was introduced in layers into the drag and compacted uniformly using hand rammers. After leveling the drag surface, it was inverted and the cope half was positioned on top. Sprue and riser pins were inserted in the cope, followed by layered sand filling and ramming. Upon completion, the sprue pins were withdrawn, gates and runners were cut, and a metallic chill was placed at one end of the mold cavity to establish a directional thermal gradient for solidification.

The aluminum scrap charge was placed in a graphite crucible and heated in the furnace to a melting temperature of approximately 580°C. Dross was skimmed from the surface, and degassing was performed using a commercial flux tablet to reduce porosity. The molten metal was poured steadily into the mold to minimize turbulence and air entrapment. The presence of the metallic chill ensured that solidification began from the chill end and progressed directionally towards the riser.

Once solidification was complete, the mold was allowed to cool to room temperature before the cope and drag was separated. The casting was removed, and excess sand was brushed off. Gates, risers, and runners were removed by cutting, and the casting surface was cleaned using wire brushing.

2.1 SAMPLE PREPARATION FOR CHARACTERIZATIONS

The tapered casting was sectioned into five portions along its length to represent different solidification zones - Chill Zone, Columnar Grain Zone and Mushy Zone. These sections were machined into specimens for mechanical and microstructural testing. A v-notch Impact specimen was machined in accordance to ASTM E28 standard. Pieces were cut for hardness and microstructural tests.

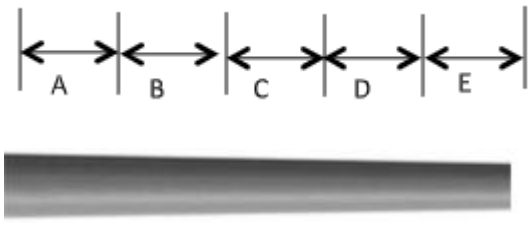


Fig. 3: Diagrammatical view of sample sectioning

2.2 IMPACT AND HARDNESS TEST

Mechanical test results were recorded in tabulated form, and microstructural measurements were compiled for comparison across different regions of the casting. Repeated measurements were taken to ensure accuracy, and deviations from expected results were investigated for possible process variations.

Impact toughness was determined using a charpy impact machine in accordance with ASTM E23. Each specimen was placed horizontal with the notch facing away from the striking pendulum. The energy absorbed in fracturing the specimen was read directly from the machine's dial in Joules.

Hardness measurements were carried out on polished surfaces using the Vickers hardness testing machine. A diamond pyramid indenter was applied under a specified load for a dwell time 10 seconds. Multiple indentations were made across different regions of the specimen to account for microstructural variation, and the mean hardness value was calculated.

2.3 MICROSTRUCTURAL EXAMINATION

Sectioned samples were subjected to metallographic operations beginning with grinding of the samples using various grits of emery paper, and polished using diamond pastes in a polishing machine. The samples were polished to a relatively mirror-like surface to enhance the clear view of the microstructures. The polished surfaces were etched in killer's reagent for 30 seconds to reveal the grain boundaries and phase distribution.Optical microscopy was used to capture images at various magnifications and the best view was selected for analysis.

3.0 DISCUSSION

3.1 IMPACT TEST RESULTS

The impact toughness of the specimens was determined using the Charpy impact tester. The results are presented in Table 2.

Table 2: Impact Test Results

Specimen	Impact Energy (J)
A	57.0
B	51.0
C	55.0
D	47.0
E	57.0

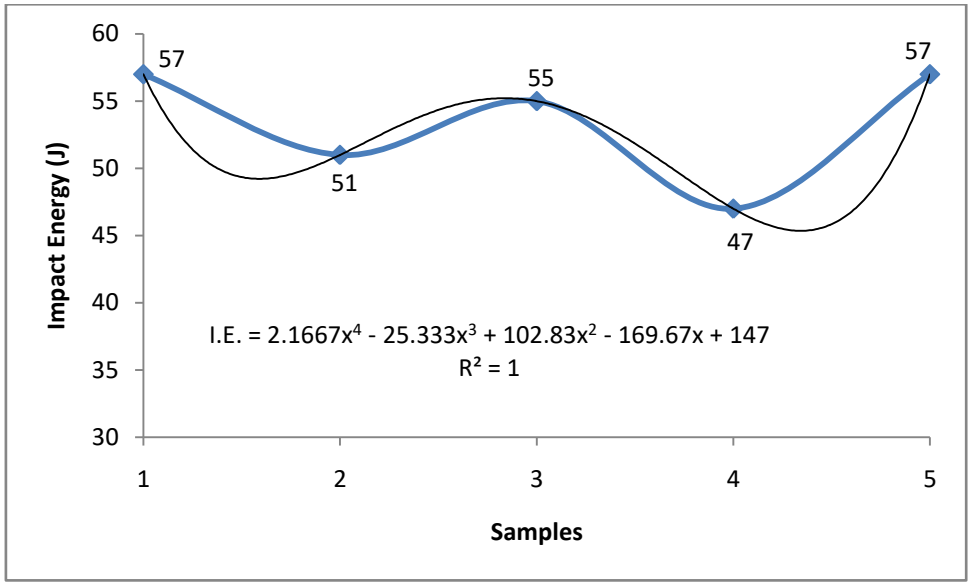


Fig. 4: Relationships between the impact energy and the rate of solidification

The impact energy results indicate that thinner section (specimen A) absorbed the highest energy (56J), showing greater resistance to fracture compared to the thicker sections. A gradual reduction in impact energy is observed towards the middle and thicker sections, with the lowest value at specimen D (45J). This trend may be attributed to variations in cooling rate during solidification, which influences grain structure and toughness.

3.2 HARDNESS TEST RESULTS

The hardness of each specimen was evaluated using the Vickers hardness tester, with two readings taken per specimen to ensure reliability. The results are shown in Table 3.

Table 3: Vickers Hardness Results

Specimen	Reading 1 (HV)	Reading 2 (HV)	Average Hardness (HV)
A	29.0	29.2	29.1
B	39.0	39.0	39.0
C	34.1	33.9	34.0
D	41.0	41.0	41.0
E	26.8	27.2	27.0

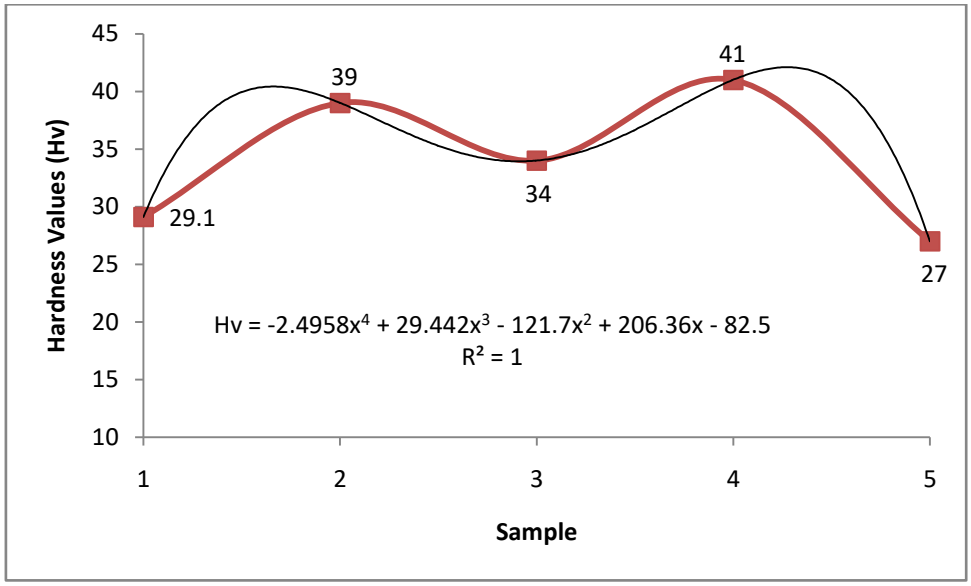


Fig. 5: Relationships between microhardness and the rate of solidification

The results reveal that hardness varied across the cast section. The highest hardness value (40.25 HV) was recorded in specimen D, while the lowest (26.25 HV) was obtained in specimen E. This variation can be associated with the cooling gradient along the tapered section. Faster cooling at thinner ends (Specimen A) produced relatively finer microstructures, while slower cooling at thicker ends (Specimen E) promoted coarse grains and reduced hardness.

3.3 MICROSTRUCTURAL EXAMINATION

The optical microstructural examination was conducted for each specimen across the tapered casting, from the thinner section (Specimen A) to the thicker section (Specimen E).

- Specimen A (Thin section): Fine equiaxed grains with a relatively uniform distribution, resulting from rapid cooling. This explains its relatively high impact energy and moderate hardness.



(a) Specimen A



(b) Specimen B



(c) Specimen C



(d) Specimen D



(e) Specimen E

Figure 4: Microstructural views of the cast at x400 magnification at various stages of solidification as indicated in Figure 3.

4.0 DISCUSSION

The experimental investigation on the directionally solidified aluminum alloy revealed a strong influence of the cooling rate along the tapered casting on both the mechanical and microstructural properties. The results from impact, hardness, tensile strength, and microstructural examinations are consistent and complementary.

1. Impact Properties: The thinner section of the casting (Specimen A) absorbed the highest impact energy (56J), while the thicker section (Specimen D) absorbed the least (45J). This indicates that rapid cooling at thinner sections refined the grain structure, producing improved toughness. Conversely, slower cooling in thicker sections promoted coarse grains and reduced toughness.
2. Hardness Properties: Hardness values increased from the thin section to the mid – thicker section, reaching a peak of 40.25HV at specimen D. However, the hardness dropped to 26.25HV at the thickest section (Specimen E). This shows that cooling rate influences dendritic growth, which controls hardness variation across the specimen.
3. Microstructural Characteristics:
    - Specimen A displayed fine equiaxed grains formed under rapid solidification, which contributed to its high impact energy.
    - Specimen B and C showed transition from fine grains to partially dendritic structures.
    - Specimen D exhibited coarse dendritic and columnar grains, which explained its higher hardness and tensile strength but lower impact energy.
    - Specimen E revealed large dendritic with evidence of porosity, reducing both hardness and tensile strength.

The study demonstrates that directional solidification creates a gradient of mechanical and microstructural properties across the casting. Faster cooling at thinner ends favours hardness and strength but reduces toughness. These findings are consistent with solidification theory, where cooling rate governs dendritic growth, grain size, and defect formation.

- Specimen B: Slightly coarser grains compared to specimen A, with improved hardness and tensile strength.
- Specimen C: Mixed grains structure with evidence of dendritic growth, indicating slower cooling in the mid – section.

- Specimen D: Coarser dendritic structure with well – developed columnar grains due to slower solidification. This explains the high hardness and tensile strength but lower impact resistance.
- Specimen E (Thick section): Large coarse dendritic grains with porosity tendencies, caused by the slowest cooling rate, this microstructure corresponds with the lowest hardness and tensile strength values.

The microstructural variations confirm that directional solidification strongly affects the mechanical properties. Faster cooling at thinner sections produced finer grains, enhancing impact toughness, while slower cooling at thicker sections led to coarse grains, which increased hardness and tensile strength but reduced toughness.

5.0 CONCLUSION

The mechanical properties of the directionally solidified aluminum alloy varied significantly along the tapered casting due to differences in cooling rate. Thinner sections of the alloy exhibited higher impact energy and finer microstructures, indicating improve toughness. Thicker sections displayed higher hardness and tensile strength due to coarse dendritic structures, but with a corresponding reduction in toughness. Microstructural analysis confirmed the presence of finer equiaxed in thinner sections and coarse dendritic/columnar grains in thicker sections, directly accounting for the observed mechanical property variations. Directional solidification therefore provides a reliable means of tailoring the mechanical properties of cast aluminum alloys by controlling cooling gradients.

REFERENCES

Campbell, J. (2015). Complete Casting Handbook. Elsevier.

Ji, S., Fan, Z., Wang, Y., & Zhang, Y, (2020).“Microstructure and mechanical properties of directionally solidified aluminum alloys.”Materials science and Engineering A, 778, 139120.

Kraft , T. L., & Lippold, J. C. (2011). “Directional solidification and its influence on mechanical properties of aluminum castings.” Metallurgical and Materials Transactions A, 42(3), 728 – 737.

M. Gell, C.P. Sullivan, and F.L. Ver Snyder: in *Solidification Technology*, J.J. Burke, M.C. Flemings, and A. Kermanpur, M. Rappaz, N. Varahram, and P. Davami: *Metall. Trans. B*, 2000, vol. 31B, pp. 1293-1304.

N. D’Souza, M.G. Ardakani, M. McLean, and B.A. Shollock: *Metall. Trans. A*, 2000, vol. 31A, pp. 2877-86.

Sigworth, G.K. (2016). “Understanding porosity formation in aluminum alloy casting.” Intrnational Journal of Metalcasting, 10(1), 45 – 57.

Suyitno, D., Katgerman, L., & Eskin, D. (2019). “Fatique behavior of directionally solidified aluminum alloys.’ Journal of Materials Processing Technology, 267,612 – 621.

T.J. Fitzgerald and R.F. Singer: *Metall. Trans. A*, 1997, vol. 28A, pp. 1377-83.