Co-relation between mechanical properties and porosity in thick, thin and thinnest sections of stepped casted workpiece using A-356 Aluminum alloy

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Abstract

A-356 aluminum alloy stepped casted workpiece were prepared with step casting technique was investigated for the mechanical properties and porosity defects using various gating elements (ingate/runner) profiles. Similarly, casted workpieces were produced using single and double gating elements with circular (vortex free), square and rectangular runner and ingate profiles. Hardness (HV) and ultimate tensile strength (UTS) of the thick section prepared from single circular runner/ingate system was more in comparison to thin and thinnest sections extracted at respective heights. Similarly, hardness and tensile strengths of thick specimen prepared from double ingate/runner having circular shape was found greater in comparison to thin and thinnest sections accordingly. SEM images depicted increase of porosity levels in thin and thinnest sections prepared from single or double within workpiece manufactured from circular runner & ingate arrangements respectively. In addition, X-ray diffraction results further revealed increase in crystallite size, hardness and tensile strength for specimens manufactured through circular profiled single or double runner/ingate arrangement. The prepared specimens also follow inverse Hall-Petch and D²/[%P statistical fit with p < 0.05 between hardness and crystallite size. Hence, the specimen with lower crystallite size or finer grains depicted attenuated mechanical properties due to higher porosity levels. In other words, D²/[%P index ratio value < 1.40 (≥95% data points follows) exhibited reductions in mechanical properties accompanied by decreasing crystallite size and vise-versa. Moreover, double gating runner & ingate combination exhibited comparatively lesser pores relative to single gating design. Hence, this study suggests double runner & ingate arrangement accompanied with circular cross-section are appropriate for large size step castings or complicated geometries production in foundries.

List of Abbreviations

| Abbreviation | Description |
|--------------|-------------|
| HV           | Vickers Hardness. |
| UTS          | Ultimate Tensile Strength. |
| HV₁₀mm       | Vickers Hardness at height/depth of 10 mm. |
| UTS₁₀mm      | Ultimate Tensile Strength at height/depth of 10 mm. |
| HV₂₀mm       | Vickers Hardness at height/depth of 20 mm. |
| UTS₂₀mm      | Ultimate Tensile Strength at height/depth of 20 mm. |
1. Introduction

Aluminium based alloys have been extensively used in several applications due to their light weight [1], relatively comparable strength [2], wear resistance and durability [3]. Aluminum alloys are exceptional due to their low density and ability to resist corrosion. Due to exceptional castability, high strength-to-weight ratio, lower manufacturing cost and better weldability aluminium alloys i.e., A356, A357, A360, A319 and others are suitable for wide range of applications [4–6]. Hence, aluminium alloys are generally used in aerospace, automotive, ship building and defence applications [7–10]. Aluminium based alloys may consist of several compositions Al-Mn, Al-Cu, Al-Cu-Li, Al-Zn-Mg, Al-Mg, higher Mg and Al-Mg-Si alloys [11].

Addition of silicon to aluminum further enhances wettability, thermal conductivity, castability and strength at higher temperatures. Several studies have been conducted on aluminum-silicon alloys by applying appropriate and optimum thermal treatments [12, 13]. Therefore, Aluminum silicon alloys i.e., A-356 are extensively used in manufacturing of engine blocks due to their phenomenal heat transfer capability [14].
Similarly, addition of certain modifiers i.e., Na, St on aluminum silicon alloys were also studied in previously conducted studies [15–17]. Moreover, the effect of pores on fatigue strength of aluminum silicon alloy was also investigated in a previous study [18]. Some previous studies conclude that variation in thickness may significantly alter mechanical properties of Aluminum- Silicon alloys [19]. Similarly, effect of alteration in gating systems was also studied [20]. However, to the best of our knowledge the effect of single and double gating system elements (runner and ingate combination) have not been investigated for the mechanical properties (hardness and ultimate tensile strength) and percentage porosity in preparation of A-356 aluminium alloy based step-castings specimens. Hence, to produce castings of adequate quality, it is extremely important to understand defect formation process in aluminium silicon alloys by changing the quantity and shape of ingate and runner system using sand castings. This research study is designed to investigate the effect of several shapes and quantity of gating system on pores (defects), hardness and tensile strength of the A-356. Hence, to achieve this goal three types of gating systems were introduced for poring the molten metal into the sand moulds. Afterwards, the step castings were prepared and specimens were subjected to microstructure and composition analysis. In addition, hardness, strength and scanning electron microscope (SEM) analysis were also analyzed. Pores were also investigated in each step castings prepared from circular, rectangular and square runner and ingate combination using scanning electron microscope (SEM) imagery using Image-J software to calculate percent porosity. Relation between hardness and UTS validated the obtained results.

2. Materials and methods

2.1. Alloy composition
Optical Emission Spectroscopy or OES is a reliable and widely used analytical technique for the determination of elemental composition of a broad range of metals. The alloy elemental composition has been estimated using same optical emission spectroscopy (OES) which is mentioned in table 1 and validates the A-356 alloy.

2.2. Gating system shapes and quantity
The gating system usually consists of pouring basin, Sprue, ladle, well, feeder/riser, Runner, ingates. Besides, dimensions of pouring basin, Sprue, ladle, well, and feeder were kept constant during the analysis (see table 2). However, in the present study, effect of various profiles and quantity of runner and ingate arrangement were used to analyze the mechanical properties and porosity in A-356 aluminium silicon alloy. Three different gating designs were used in the following study which includes (refer to figure 1):

1. Single & double circular runner and ingate (SC) and (DC).
2. Single & double square runner and ingate (SS) and (DS)
3. Single & double Rectangular runner and ingate (SR) and (DR).

Workpiece prepared from single runner/ingate having thick, thin and thinnest segments were represented by SC-1, SC-2 and SC-3 accordingly. Similarly, the specimens prepared from two circular runner/ingate

| Table 1. Elemental composition of A-356 (LM-25) aluminium alloy before casting. |
|---------------------------------|--------|------|------|-----|-----|-----|-----|-----|
| Chemicals                      | Al     | Si   | Fe   | Mg  | Ti  | Mn  | Zn  | Cu  |
| Compositions (%Weight)         | 91.75  | 6.91 | 0.19 | 0.30| 0.25| 0.25| 0.10| 0.25|

| Table 2. Various critical parameters related to casting. |
|---------------------------------------------------------|
| Parameter                        | Values                                      |
| Gating system                     | Pressurized gating                         |
| Gate type                         | Bottom gating system                       |
| Runner type                       | Square/rectangular/circular                |
| Sprue type                        | Tapered circular cross section             |
| Filling time                      | 37 ± 2 s                                    |
| Gating ratio                      | 1 : 2 : 1                                   |
| Sprue area                        | 35 mm²                                      |
| Casting weight                    | 1.628 kg                                    |

Similarly, addition of certain modifiers i.e., Na, St on aluminum silicon alloys were also studied in previously conducted studies [15–17]. Moreover, the effect of pores on fatigue strength of aluminum silicon alloy was also investigated in a previous study [18]. Some previous studies conclude that variation in thickness may significantly alter mechanical properties of Aluminum- Silicon alloys [19]. Similarly, effect of alteration in gating systems was also studied [20]. However, to the best of our knowledge the effect of single and double gating system elements (runner and ingate combination) have not been investigated for the mechanical properties (hardness and ultimate tensile strength) and percentage porosity in preparation of A-356 aluminium alloy based step-castings specimens. Hence, to produce castings of adequate quality, it is extremely important to understand defect formation process in aluminium silicon alloys by changing the quantity and shape of ingate and runner system using sand castings.
combination having thick, thin and thinnest portions were shown by DC-1, DC-2 and DC-3 respectively. Moreover, samples produced from single and double square contour runner/ingate in thick, thin and thinnest sections were represented by SS-1, SS-2, SS-3, DS-1, DS-2 and DS-3 correspondingly. Additionally, workpiece specimens prepared from single and double rectangular profile runner/ingate in thick, thin and thinnest fragments were described by SR-1, SR-2, SR-3, DR-1, DR-2 and DR-3 respectively. Thick, thin and thinnest segments of stepped casted workpiece were having thicknesses of 60, 40 and 20 mm accordingly.

2.3. Mathematical calculations
In this work, proper dimensioning of gating system has been performed by combination of Chvorinov’s and Wlodawer methods which is also known as Modulus method [21–23]. Modulus is defined as the ratio of the volume to the cooling surface area of the casting (or a part of the casting) or the feeder [24, 25].

\[ M = \frac{V}{A} \]  

(1)

Where, \( V \) is the volume of casting, or feeder, \( A \) is the cooling surface area. In addition, Chvorinov’s rule state that, solidification time increases as the square of volume to area ratio increase, and hence \( M \), increase [23, 26].

\[ T = C \times \left( \frac{V}{CS} \right)^2 \]  

(2)

Where \( T \) is the solidification time, and \( C \) is constant. Moreover, Wlodawer’s technique suggests the modulus of the feeder should be greater than that of the casting. Thus, using a 20% factor of safety,

\[ MF \geq 1.2 \; MC \]  

(3)

Figure 1. CAD models with stepped casting workpieces having (a) Single circular runner & ingate system (b) Double circular runner & ingate system. (c) Single square runner & ingate system (d) Double square runner & ingate system (e) Single rectangular runner & ingate system (f) Double rectangular runner & ingate system.
Where, MF and MC are modulus of feeder and casting respectively \([21, 27]\). Pouring rate formula for non-ferrous gating is estimated by undermentioned formula \([28]\):

\[
 R = b \sqrt{W}
\]  

(4)

Where \(R\) and \(b\) are pouring rate and constant accordingly. Typical values of \(b\) are easily available in literature. Some of the critical dimensioning ratios from Chastain’s Foundry Manual used are under-mentioned:

(a) Choke or sprue area at the bottom is approximately equivalent to \(1/5\)th of the area of the well.

(b) The well shall be two times greater than runner depth.

(c) Sprue top area was evaluated as five times greater than choke area i.e., \(5 \times Ac\)

In addition, during designing of gating elements the compliance of Modulus criteria was ensured which can be mathematically written as:

\[
 MR > MC > Mru > MI 
\]  

(5)

In above-mentioned relation \(MR, MC, M鲁\) and \(MI\) are modulus of riser, casting, runner and ingate respectively. Additionally, choke area has been calculated using under-mentioned formula \([16]\):

\[
 Ac = \frac{W}{\mu T \sqrt{2gSL}}
\]  

(6)

Chvorinov’s rule, which states that total solidification time \(T_s\), can be computed by:

\[
 T_s = B(V/A)^n
\]  

(7)

where \(n = 1.5\) to \(2.0\)

\[
 Re = \frac{\rho VD}{\mu}
\]  

(8)

Value of \(Re\) comes out to be \(6\) which is much below \(2000\). Therefore, the gating system design calculations are considered to be appropriate.

2.4. Specimen preparation

Initially, Computer aided design (CAD) based models of stepped workpieces attached with sprue, ladle and feeder were prepared which are shown in figure 1 and 2. In the second step, wooden patterns were prepared in the pattern making shop (consult figure 3(a)). Moulds were prepared for sand casting purpose as shown in
figures 3(b) and (c). Silica sand (SiO$_2$) is mixed with binder to help and maintain the shape of the mould cavity. Sand is inexpensive and highly resistant to high temperatures; allowing molten metals to be cast at elevated temperatures. Typical composition of the mixture is 90% silica sand, 3% water, and 7% clay or binder. After moulds preparation, the aluminium alloy A-356 was melted in a silicon-graphite crucible in a furnace at a temperature around 790 $\pm$ 10°C. Besides, all temperature measurements during entire metal melting and casting process were made and recorded using temperature gun (see figures 3(d)–(f)). Finally, tensile strength specimens were prepared in accordance with ASTM-E8 standards at 10 and 20 mm elevation from datum point at thick, thin and thinnest portions. Specimens were further machined from the stepped casting, as per dimensions mentioned in ASTM-E8.

2.5. Material characterization

X-ray diffraction (XRD) has been performed using the x-ray diffractometer. Obtained peaks were compared with standard peaks of A-356 alloys. The matching of peaks will affirm that the material is A-356 aluminum alloy using JCPDS cards i.e., Al: JCPDS 01–1180 and Si: JCPDS 03–0544 respectively. Average crystallite was also estimated using modified Scherrer formula $^{29, 30}$:

$$
\beta_{hkl} = \frac{k\lambda}{L \cos \theta} + 4\eta \tan \theta
$$

Rearranging the equation (8), which can be written as:

$$
\beta_{hkl} \cos \theta = \frac{k\lambda}{L} + 4\eta \sin \theta
$$

Hence, $\beta_{hkl}$ was plotted against $\sin \Theta$ to extract average crystal size from the $y$-intercept of the relation. In the aforementioned relation, $k$ and $\Theta$ are the constants (having value of 0.94) and Bragg angle respectively.

Tensile test is a versatile characterization technique; it is a well-known method to extract information about the materials strength and deformation properties in a single test. Room temperature uniaxial tensile tests were performed on ASTM E8–04 samples machined from the aluminum A-356 cast alloy. Each piece was clamped on the tensometer capable of producing a load-extension graph on attached graph paper. A graphical result of the applied load against extension was obtained from the auto-graphic reading drawn by the Shimadzu Autograph AG-IS tensile testing machine, and the maximum load was obtained and corresponding stress calculated.

The hardness tests of all the samples in thick, thin and thinnest portions using a Vickers hardness testing machine at specimens extracted from 10 and 20 mm vertical elevation respectively. For each composition, six
Indentations were taken and average value was reported. The Vickers hardness test method consists of indenting the test material with a diamond indenter, pyramidal in shape with a square base and subjected to a load of 1 to 100 kgf. The Vickers hardness test method also referred to as a micro hardness test method is mostly used for small parts, thin sections. In our case, Low load Vickers hardness testes (HV-30) is used for measuring the hardness of the samples. Aluminum being soft metal hence 10kgf load was applied on each specimens and dwell time was selected 5 section.

2.6. Porosity calculation through Image-J software

Image-J is an open source Java-based image processing program which is used for 2D porosity calculations. In our case it has been used to calculate the pore sizes for aluminium alloy-based specimen. The software version 1.52 has been used in order to calculate 2D porosity in all the casted samples.

The basic steps involved in porosity determination using image-J are mentioned step-wise:

1. Opening of the image in Image-J software.
2. Scale and units of the image were adjusted.
3. Images were binarized using thresholding procedure. Thresholding of the image makes the pores colourful. In contrast, rest of the image became grey.
4. After capturing the porosity in the micrographs, percent porosity area, ferret diameter for pores, maximum and minimum pores sizes were calculated.
5. All the above mentioned steps were used to calculate porosity in each and every specimen casted through circular, square and rectangular runner and ingate system.

3. Results

3.1. X-ray diffraction characterization

XRD analysis confirmed the microstructure of A-356 alloy. The peaks obtained from the XRD were Si (111), Al (111), Al (200), Si (311), Al (220), Al (311) and Al (222) at double Bragg angles having values of 27.6°, 34.75°, 39.1°, 40.25°, 44.8°, 47.5°, 56.25°, 58.3°, 65.3° and 78. 35° respectively (see figures 4–6). These peaks has been confirmed from the existing literature for the A-356 alloys [31–33]. Moreover, some inter-metallic phases were also observed in specimens prepared from rectangular shaped runner & ingate arrangement which were also supported by literature [34].

Figure 4. X-ray diffraction of specimens casted through Single & Double Circular runner/ingate system (a) SC-1 (b) SC-2 (c) SC-3 (d) DC-1 (e) DC-2 (f) DC-3.
3.2. Tensile testing

Gating system elements play an important role on the quality and strength of casted aluminum alloy [28]. Single circular runner and ingate combination influenced the ultimate tensile strength (UTS) of 283.0 ± 6.10, 221.0 ± 7.5 and 216.0 ± 7.6 MPa for thick (SC-110 mm), thin (SC-210 mm) and thinnest section (SC-310 mm) respectively. Similarly, tensile strength was determined as 279.0 ± 6.5, 219.5 ± 7.6, 205.6 ± 7.5, 230.3 ± 6.5, 201.6 ± 6.2 and 212.4 ± 6.2 MPa accordingly (consult figure 7). Besides, samples
uprooted from $UTS_{20mm}$ $219.6 \pm 6.9, 218.9 \pm 6.9, 201.0 \pm 7.2, 225.5 \pm 7.5, 192.0 \pm 6.5$ and $209 \pm 6.2$ MPa. Similarly, $UTS$ depicted by rectangular shaped runner/ingate combination at 10 and 20 mm were recorded to be $198.2 \pm 5.5, 155.5 \pm 5.5, 121.5 \pm 6.5, 203.75 \pm 5.3, 185.9 \pm 6.2, 150.5 \pm 5.5, 121.0 \pm 6.5, 199.9 \pm 6.5, 124.0 \pm 5.4$ and $131.0 \pm 5.3$ MPa. Furthermore, the results reveal that $UTS$ deteriorates in the thin and thinnest portions in comparison to thick portion in specimens prepared from all the three profiles i.e., circular, square and rectangular. In general, specimens prepared of circular runner and ingates shows enhanced $UTS$ in comparison to square and rectangular runner and ingate combination.

### 3.3. Hardness testing

Single circular runner and ingate combination depicted higher hardness values of $106.0 \pm 4.5, 104.8 \pm 4.3, 94.0 \pm 3.5, 93.5 \pm 3.0, 90.0 \pm 2.9$ and $89 \pm 3.0$ HV for specimen taken from 10 and 20 mm respectively at thick (SC-1), thin (SC-2) and thinnest section (SC-3) respectively. The result shows that hardness values deceases by increase of distance from ingate and runner combination. In contrast, double circular runners displayed hardness of $107.5 \pm 4.3, 105.0 \pm 4.7, 95.4 \pm 3.3, 93.8 \pm 3.5, 98.0 \pm 3.5$ and $97.5 \pm 3.0$ HV for each identified sections (10 and 20 mm) respectively (see figure 8). These results confirm that with provision of additional runner and ingate combination, hardness slightly improved in comparison to single runner/ingate. Moreover, square shaped single and double runner/ingate assembly exhibited hardness values of $97.65 \pm 3.1$ (SS-110mm), $93.67 \pm 3.0$ (SS-210mm), $93.85 \pm 3.1$ (SS-220mm), $90 \pm 3.3$ (SS-310mm), $88.3 \pm 2.7$ (SS-320mm), $84.0 \pm 3.0$ (SS-200mm), $97.6 \pm 3.1$ (DS-110mm), $94.6 \pm 3.1$ (DS-120mm), $84.0 \pm 2.9$ (DS-210mm), $78.0 \pm 3.3$ (DS-220mm), $90.0 \pm 3.2$ (DS-310mm) and $88.5 \pm 3.5$ HV (DS-320mm) accordingly. Similarly, single and double runner/ingate
combination having rectangular shape resulted in 81.5 ± 3.60 (SR-110mm), 78.7 ± 3.7 (SR-120mm), 52.2 ± 3.5 (SR-210mm), 51.2 ± 3.55 (SR-220mm), 51.6 ± 3.4 (SR-310mm), 50.9 ± 3.3 (SR-320mm), 85.5 ± 3.1 (DR-110mm), 83.2 ± 3.3 (DR-120mm), 54.3 ± 3.1 (DR-210mm), 51.3 ± 3.3 (DR-220mm) and 62.4 ± 3.6 (DR-310mm) and 60.2 ± 3.7 HV (DR-320mm) that represents lowest values among the three profiles of runner/ingate.

3.4. SEM and pore estimation

SEM images shows that A-356 sample prepared from circular shaped runner and ingate was having much balanced microstructure accompanied with proper dispersion of silicon in thin, thinner and thinnest sections (see figures 9 and 10). Conversely, specimens manufactured from square and rectangular profile runner/ingate illustrates higher porosity in SEM images (consult figures 11–14). However, slight porosity was detected in specimens extracted at 10 and 20 mm are 0.081 (SC-110mm), 0.077 (SC-120mm), 0.114 (SC-210mm), 0.101 (SC-220mm), 0.158% (SC-310mm) and 0.162% (SC-320mm) respectively using integration of SEM and image-J.
software (refer to figure 15). Furthermore, with addition of one additional circular runner and ingate assembly also exhibits low porosity levels 0.079 (DC-110mm), 0.0765 (DC-120mm), 0.236 (DC-210mm), 0.233 (DC-220mm), 0.145 (DC-310mm) and 0.122% (DC-320mm) accordingly. In contrast, specimen prepared from single and double square runner/ingate system relatively show higher porosity percentage when compared with circular runner/ingate system. In single square runner/ingate combination exhibited 0.475 (10 mm), 0.378 (20 mm), 0.531 (10 mm), 0.401 (20 mm), 1.115 (10 mm) and 1.06% (20 mm) for thick, thin and thinnest portions accordingly. Besides, double square shaped runner/ingate combination revealed 0.171, 1.857 and 0.348% porosity subsequently (kindly see figure 15). In contrast, single and double rectangular runner/ingate combination reveals pore percentages of 3.49 (SR-110mm), 3.11 (SR-120mm), 4.75 (SR-210mm), 4.38 (SR-220mm), 6.86 (SR-310mm), 6.48 (SR-320mm), 1.2 (DR-110mm), 1.179 (DR-120mm), 3.21 (DR-210mm), 3.06 (DR-220mm), 2.739 (DR-310mm) and 2.52% (DR-320mm) respectively (see figure 15). Quantity of pores in specified area has increased in specimens manufactured from double rectangular shaped runners/ingate design except the thin region.

Figure 11. SEM micrographs of specimens casted through single square runner/ingate arrangement (a) thick (b) thin (c) thinnest sections. SEM micrographs after integration with image-J software showing porosity in samples casted through single square runner and ingate system (d) thick (e) thin (f) thinnest portions.

Figure 12. SEM micrographs of specimens casted through double square runner/ingate arrangement (a) thick (b) thin (c) thinnest sections. SEM micrographs after integration with image-J software showing porosity in samples casted through double square runner and ingate system (d) thick (e) thin (f) thinnest portions.
3.5. Crystallite size and its co-relation

Crystallite sizes were estimated for specimens using procedure mentioned in experimental section. Crystallite size decreases in all the specimens when thick sections are compared with corresponding thin and thinnest sections (kindly refer to figure 16). Hence, this further implies that relation between $D$ and $H$ is not governed by conventional Hall-Petch relation. Furthermore, decrease in hardness of A-356 alloy was observed accompanied by decreasing crystallite size ($D$) i.e., inverse Hall-Petch relation (see figure 17). Hence, the inverse Hall-Petch relation was fitted with confidence level of 95% (see table 3). However, more precise and accurate statistical relation to describe crystallite size and hardness has been given in figure 18. Additionally, hardness is related to ratio of squared crystallite size and percent surface porosity ($D^2/\%P$) supported with noticeably higher $F$-value compared to inverse Hall-Petch relation (Consult table 3 and 4).

Figure 13. SEM micrographs of specimens casted through single rectangular runner/ingate arrangement (a) thick (b) thin (c) thinnest sections. SEM micrographs after integration with image-J software showing porosity in samples casted through single rectangular runner and ingate system (d) thick (e) thin (f) thinnest portions.

Figure 14. SEM micrographs of specimens casted through double rectangular runner/ingate arrangement (a) thick (b) thin (c) thinnest sections. SEM micrographs after integration with image-J software showing porosity in samples casted through double rectangular runner and ingate system (d) thick (e) thin (f) thinnest portions.
Figure 15. Porosity levels / percentage calculated using ImageJ software (a) 10 mm & (b) 20 mm height accordingly.

Figure 16. Crystalite size at thick, thin and thinnest segments at (a) 10 mm and (b) 20 mm heights correspondingly.

Figure 17. Inverse Hall-Petch relation plotted between crystallite size and hardness (a) 10 mm and (b) 20 mm height accordingly.
4. Discussions

Hardness and tensile strength portrayed a prominent decrement in the portion away from thick section in single circular, square and rectangular shaped gating elements. Minimum values of both the properties i.e., hardness and UTS are observed at thinnest portion in single gating systems. This decrease in the properties of the thin and thinnest sections can be attributed to decrease in flow velocity and higher heat transfer rate of molten metal which slightly results in more porosity. The enhancement in heat transfer and solidification time with rigorous metal front collisions enhance turbulence at thin and thinnest sections, which is also validated by estimations performed by Schwartz and Tiryakioğlu et al., 1997 [24, 34]. Chvorinov’s rule further justifies the fact that solidification time varies directly with volume to surface area ratio and also depends upon the geometry of the casting [35]. Furthermore, higher percentage of voids were evidenced by SEM micro-graphs, which further

Table 3. Regression analysis of inverse hall-petch relation for specimens extracted from 10 and 20 mm.

| Specimen height | DOF | SS      | MS      | F Value | F-Value > F(v1,v2,α) | p-Value |
|-----------------|-----|---------|---------|---------|-----------------------|---------|
| 10 mm Regression | 2   | 18144.9832 | 9072.492  | 481.5551 | 481.55 > 3.63         | <0.05   |
| Residual        | 16  | 301.43978 | 18.83999 |         |                       |         |
| Uncorrected total | 18  | 18446.42298 |         |         |                       |         |
| Corrected total | 17  | 908.24521 |         |         |                       |         |
| 20 mm Regression | 2   | 17000.02729 | 8500.014  | 373.4278 | 373.42 > 3.63         | <0.05   |
| Residual        | 16  | 364.19412 | 22.76213 |         |                       |         |
| Uncorrected total | 18  | 17364.22141 |         |         |                       |         |
| Corrected total | 17  | 891.59121 |         |         |                       |         |

Table 4. Regression analysis of $D^2/%P$ against hardness for specimens extracted from 10 and 20 mm.

| Specimen height | DOF | SS      | MS      | F Value | F-Value > F(v1,v2,α) | p-Value |
|-----------------|-----|---------|---------|---------|-----------------------|---------|
| 10 mm Regression | 2   | 18333.73335 | 9166.867  | 1301.538 | 1301.5 > 3.63         | <0.05   |
| Residual        | 16  | 112.68964 | 7.0431  |         |                       |         |
| Uncorrected total | 18  | 18446.42298 |         |         |                       |         |
| Corrected total | 17  | 908.24521 |         |         |                       |         |
| 20 mm Regression | 2   | 16786.44941 | 8393.225  | 1421.895 | 1421.8 > 3.63         | <0.05   |
| Residual        | 16  | 94.44554 | 5.90285 |         |                       |         |
| Uncorrected total | 18  | 16880.89495 |         |         |                       |         |
| Corrected total | 17  | 872.1232  |         |         |                       |         |
authenticates the decrement in mechanical properties in thin and thinnest sections within single runner/ingate combination (refer to figures 9–15). Single square and rectangular gating elements (ingate/runner) combination indicated a decline in the mechanical properties and higher porosity levels due to higher turbulence and molten metal velocity ($\geq 0.5 \text{ m s}^{-1}$) [28, 36]. In contrast, double ingate/runner combination depicted a sharp decrease at thin section probably due to intersection of two molten metal up-fronts. Mixing of these metal fronts enhances the turbulence which as a consequence yields minimum hardness; tensile strength and maximum percent porosity (please refer figures 9–12 and 15). SEM also supports the increase in porosity at thin section accordingly which also confirms the decrease in hardness and tensile strength at this particular portion using double ingate/runner arrangement (consult figures 10, 12 and 15).

Specimens prepared from circular shaped runner/ingate combination exhibited higher average crystallite size in comparison to square or rectangular (see figure 13). Hence, the results illustrate that higher percentage of surface porosity, which considerably affects the mechanical (hardness and tensile strength) properties (consult figures 7, 8 and 15). Additionally, literature also supports the validity of inverse Hall–Petch relation at crystallite sizes $\sim \leq 30 \text{ nm}$ [37]. Additionally, the outcome of A-356 alloy also shows the dependence of hardness and tensile strength upon square of crystallite size divided by percent surface porosity ($D^2/P$). Previously published literature supports the facts that at higher cooling rate finer grains are nucleated which depict higher hardness values [38]. However, in our case higher percentage of pores inside the step casted workpiece prepared at height of 10 mm within the thick, thin and thinnest sections have much higher $D^2/P$ index ratio $\sim \geq 1.40$ (kindly see figures 18 and 19). Proper co-relation has been established between hardness and the ratio of squared crystallite size/$P$ porosity (consult figure 18). The results deducts that for $D^2/P$ index ratio $\geq 1.40$ conventional trends in mechanical properties were not evidenced (see figure 20). Additionally, $D^2/P$ index ratio $\sim \geq 1.40$ between each corresponding thick, thin and thinnest sections at 10 and 20 mm also depicted decline in crystallite size which means reduction in crystalline nature of A-356 (see figure 16). Hence, even finer grains in thin and thinnest portions for all three shapes having $D^2/P$ index ratio $\sim \geq 1.40$ exhibited much lower values of hardness and tensile strength at heights of 10 and 20 mm individually. In contrast, thick, thin and thinnest portions for all three runner/ingate arrangements taken at 20 mm were having lower mechanical properties (UTS and $HV$) when compared with specimens prepared from 10 mm height. Moreover, XRD illustrates a sharp increase in crystallinity in specimens prepared from circular runner/ingate compared to square or rectangular combination (runner/ingate) (see figure 6). Besides, improvement in crystalline nature of specimen at 20 mm in comparison to samples extracted from 10 mm further employs that hardness and UTS may decrease according to conventional material theory [39, 40]. Likewise, intermetallic phases were evidenced in XRD of the specimens prepared from rectangular runner/ingate arrangement. Hence, presence of these intermetallics may further reduce mechanical properties [41].

Relation between hardness and UTS has been validated using the available literature. Previous studies suggest that tensile strength is $2.2 \sim 2.8$ times greater than hardness in case of aluminium alloys [42, 43]. Therefore, both the quantities were plotted for each specimen prepared from circular, square and rectangular

![Figure 19. $D^2/P$ index calculation between (a) thick, thin and thinnest portions at 10 mm height (b) thick, thin and thinnest portions at 20 mm height.](image-url)
shapes, and it also shows the conformance of our results with the previous literature. (Kindly consult figures 21(a)–(c)).

5. Conclusion

In this paper effect of circular, square and rectangular runner & ingate profiles with single and double gating arrangements was comprehensively investigated. The main findings of the study is mentioned below:
1. Hardness of thin and thinnest portions manufactured by single circular runner/ingate almost decreased around 11 and 15% in comparison to thick casted section. However, thick specimens prepared from single square and rectangular profiled runner/ingate arrangement exhibited considerable decrement of 12.3% and 20% approximately when compared with thick specimen manufactured from circular profile. The thin and thinnest portions manufactured by single circular runner/ingate almost exhibited deterioration in UTS i.e., ~9.5% and 15.5% in comparison to thick casted section. However, thick specimens prepared from single square and rectangular profiled runner/ingate assembly had shown substantial reduction of ~11% and 21% approximately in UTS, when compared with maximum thickness specimen manufactured from circular profile.

2. Percentage porosity depicted a considerable enhancement of ~40 and 100% in thin and thinnest portions prepared from single circular shaped runner/ingate arrangement, when compared with thick casted specimen. Nevertheless, % porosity of thick sections of samples prepared from single square and rectangular profiled runner/ingate has shown ~230% and 1050% enhancement compared to thick section casted by circular runner/ingate assembly. In addition, thin and thinnest specimens casted by two runner/ingate circular shaped assembly exhibited significant increase in porosity levels to ~40% and 50% in comparison to thick portion manufactured from the same gating design arrangement. Additionally, porosity level considerably increments to 105% and 3250% respectively, in maximum thickness specimens prepared from two square and rectangular runner/ingate combination in comparison to thick section casted from double circular gating arrangement. Hence, the porosity levels support the values of hardness and UTS accordingly.

3. Mechanical properties (Hardness and UTS) are dependent upon \(D^2/P\) ratio between two regions. In case the \(D^2/P\) ratio \(\geq 1.4\) the conventional increase or decrease will not be exhibited in A-356 alloy (most of data points follows this ratio). Instead more crystalline region will depict higher mechanical properties. Additionally, conventional trends in properties are observed for \(D^2/P\) ratio < 1.4.

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**Data availability statement**

The data generated and/or analysed during the current study are not publicly available for legal/ethical reasons but are available from the corresponding author on reasonable request.

**Appendix**

**A1. Increment/decrement calculation**

Increment and decrement percentage can be calculated using the formulas given below:

The formula for percent increment is as follows:

\[
\% \text{ increment} = \text{Start Value} \times (1 + \% \text{ of Start or stable Value})
\]  

(A-1)

Similarly, the formula for percent decrement is as follows:

\[
\% \text{ decrement} = \text{Start Value} \times (1 - \% \text{ of Start or stable Value})
\]  

(A-2)

**A2. Miscellaneous informations**

\(\text{Sprue Top Area} = A_2 = 372 \text{ mm}^2\)

Multiplying by a factor of 1.2 as suggested by Prof. John Campbell

\(\text{Sprue Top Area} = A_2 = 446.4 \text{ mm}^2\)

\(\text{Dia of Sprue Top Area} = D_c = 24 \text{ mm}\)
A3. Hardness and tensile strength data

|        | 10 mm HV ± S.D. (HV) | 20 mm HV ± S.D. (HV) | 10 mm Tensile ± S.D. (MPa) | 20 mm Tensile ± S.D. (MPa) |
|--------|----------------------|----------------------|-----------------------------|-----------------------------|
| SC1    | 106.00 ± 4.50        | 104.80 ± 4.25        | SC1 283.02 ± 6.10           | SC1 279.10 ± 6.50           |
| SC2    | 94.0 ± 3.30          | 93.50 ± 3.15         | SC2 220.90 ± 7.50           | SC2 219.50 ± 7.60           |
| SC3    | 90.0 ± 2.91          | 89.00 ± 3.09         | SC3 216.00 ± 7.60           | SC3 209.50 ± 7.72           |
| DC1    | 107.50 ± 4.30        | 104.95 ± 4.75        | DC1 284.62 ± 6.35           | DC1 281.40 ± 6.45           |
| DC2    | 95.4 ± 3.30          | 93.78 ± 3.56         | DC2 224.19 ± 7.23           | DC2 221.60 ± 7.13           |
| DC3    | 98.00 ± 3.50         | 97.45 ± 2.97         | DC3 240.56 ± 7.24           | DC3 232.00 ± 7.44           |
| SS1    | 97.60 ± 3.10         | 93.67 ± 3.06         | SS1 229.36 ± 6.91           | SS1 219.89 ± 6.99           |
| SS2    | 93.85 ± 3.14         | 90.00 ± 3.23         | SS2 221.47 ± 7.00           | SS2 218.90 ± 6.90           |
| SS3    | 88.26 ± 2.70         | 84.00 ± 2.93         | SS3 205.65 ± 7.50           | SS3 201.00 ± 7.21           |
| DS1    | 97.60 ± 3.34         | 94.60 ± 3.19         | DS1 230.34 ± 6.30           | DS1 225.30 ± 7.50           |
| DS2    | 84.00 ± 3.10         | 78.00 ± 3.25         | DS2 201.60 ± 6.23           | DS2 192.00 ± 6.50           |
| DS3    | 90.00 ± 3.20         | 88.50 ± 3.46         | DS3 212.41 ± 6.21           | DS3 208.90 ± 6.23           |
| SR1    | 81.50 ± 3.60         | 78.70 ± 3.70         | SR1 198.18 ± 5.50           | SR1 185.98 ± 6.21           |
| SR2    | 52.20 ± 3.50         | 51.23 ± 3.53         | SR2 155.30 ± 5.53           | SR2 150.50 ± 5.50           |
| SR3    | 51.60 ± 3.40         | 50.91 ± 3.29         | SR3 121.50 ± 6.55           | SR3 120.70 ± 5.55           |
| DR1    | 85.50 ± 3.10         | 83.20 ± 3.30         | DR1 203.75 ± 5.31           | DR1 199.87 ± 6.55           |
| DR2    | 54.30 ± 3.13         | 51.30 ± 3.25         | DR2 128.25 ± 5.24           | DR2 124.00 ± 5.44           |
| DR3    | 62.40 ± 3.60         | 66.20 ± 3.70         | DR3 138.50 ± 5.21           | DR3 131.00 ± 5.31           |

A4. Stress-strain graphs

UTS values are determined by stress-strain curves. The stress-strain graphs for all the cases i.e., circular, square and rectangular are given in figure A1.
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