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IMPACT OF GATING SYSTEM DESIGN ON MECHANICAL PROPERTIES OF ALUMINIUM SAND CASTINGS

Marko ZAGORIČNIK[1], Lazar KOVAČEVIĆ[1], Vladimir TEREK[1], Zoran BOBIĆ[1], Pal TEREK[1]

Orcid: 0000-0003-0798-456X; **Orcid:** 0000-0002-0843-4984; **Orcid:** 0000-0001-9994-6039;

[1]University of Novi Sad, Faculty of Technical Sciences, Serbia,

*Corresponding author: zagoricnik@uns.ac.rs

Abstract: *Aluminium alloys are extensively employed across modern industries, appreciated for their advantageous combination of low weight, corrosion resistance, strength, and ductility. Nonetheless, casting defects—including inclusions, porosity, hydrogen absorption, and particularly bifilms—can significantly compromise the mechanical properties of cast components. The present investigation centres on bifilm-related defects, which originate from the oxidation behaviour of aluminium alloys. Upon exposure to air, a thin oxide layer instantly forms on the molten metal surface. When disrupted, this film is immediately replaced by a new one, and such layers can become entrained within the melt during various stages of processing. Once inside the liquid metal, these oxide films retain their structural integrity due to their inert nature, remaining as compacted and folded entities that do not dissolve or disperse. Their presence has a pronounced negative impact on mechanical properties and can result in internal discontinuities that reduce mechanical properties and manifest as leak paths after machining. While bifilms can be introduced during melting, charging, or refining, the pouring phase presents a critical opportunity for their entrapment. Thus, the design of the gating system becomes essential. In this preliminary study, the role of flow dynamics during mould filling was examined by comparing two distinctly configured gating systems in sand casting of aluminium alloy: a top-gated setup promoting turbulent flow, and a bottom-gated arrangement intended to minimize flow disturbance. Advanced simulation using Magmasoft software confirmed the expected flow behaviours, illustrating greater splashing and air entrapment in the top-gated configuration. Following casting, samples were machined and subjected to tensile testing. Results demonstrated a statistically significant increase in ultimate tensile strength for specimens produced via the bottom-gated system. This exploratory experiment lays the groundwork for continued investigations into bifilm mitigation through optimized gating design.*

Keywords: *Bifilms, casting, entrainment, aluminium alloy, gating systems*

1. INTRODUCTION

Many liquid metals are not actually pure liquid. Most of them contain floating solid phases that can reduce the mechanical properties of castings. Much evidence applies to aluminium and its alloys, where research has been focused, but steels and nickel alloys also may suffer from these defects [1]. Additionally, aluminium alloys are especially vulnerable to entrainment, a process in which the thin oxide layer on the surface of the melt enters the liquid and folds in on itself, remaining crumpled during the solidification, and acting as a crack during exploitation. Prof. Cambell has made significant research in this field [2,3] highlighting the effect of entrainment defects on castings.

How does entrainment happen? When a molten metal is poured, its surface area increases as it flows. Due to the high reactivity of aluminium alloys oxides immediately form on the newly available surface. If the surface ever contracts, the oxide layers cannot merge like surface of the molten metal, and they crumple and fold on themselves. Similarly, if the melt splashes, droplets oxidise in the air and when they fall back to the melt they introduce the oxides to the bulk. Poor gating system design causes the melt to flow uncontrollably: swirling, splashing, eroding the mould, and trapping air as it flows. This process introduces large amounts of surface oxides and sand inclusions into the casting. Due to the similar density of its oxides compared to the liquid aluminium, these inclusions float up very slowly and often remain in the castings. Careful design of filling systems can minimize turbulence and splashing, greatly reducing the entrainment defects [2,3].

Previous research on bifilms, conducted on Al-Si-Mg alloys yielded results that indicate the negative effect of bifilms on the scatter of mechanical properties of castings. These experiments compared different gating systems which were designed to promote or reduce the creation and entrainment of surface oxides [4,5]. Another research, on Cu-Al alloy [6] also designed an experiment that compared the effects of different gating systems on bifilm creation. The results have shown similar trends. Another research on Al-Cu alloy [7], compared the tensile properties of top gated, and tilt poured specimens, and indicated that the increased bifilm generation in the top gated system was responsible for the scatter of mechanical properties.

This paper is a fundamental testing of an experimental setup and serves as a replication study for similar previous work [4,5,6,7]. Unlike prior studies that used more robust gating systems, this experiment utilized a detailed, and more efficient design to optimize metal utilization. This study focused on establishing a reliable methodology for investigating the effects of bifilms in highly reactive (oxidizing) aluminium alloys.

2. MATERIALS AND METHODS

In this study, Al-Si alloy was used to produce standard tensile strength test pieces using two different filling system designs, namely one bottom gated and one top gated. To make the moulding easier, the test pieces were cast as cylindrical bars with diameter of 20 mm. Multiple bars were cast simultaneously so that the results can be averaged. Both filling systems included the same spacing and position of the test pieces in the mould, to minimize the difference in cooling conditions in the mould.

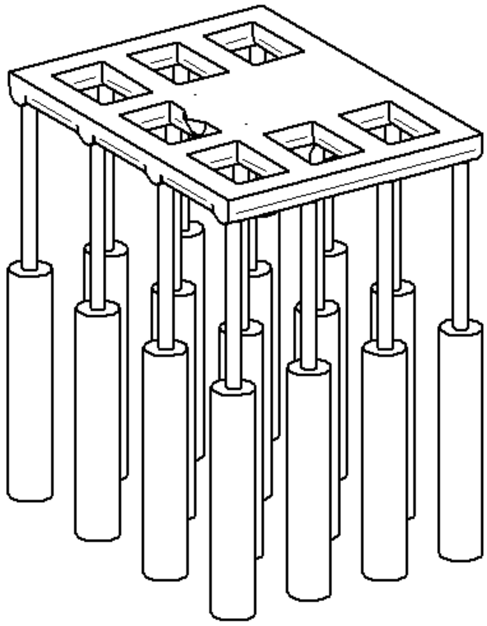

Figure **1.** CAD drawing of the top gated system

The experimental design of top gated system is given in Fig. 1. The chosen geometry is a representative of widespread methoding practice in foundries that prioritize minimal expenditures and prefer quick and simple solutions. This design has a hemispherical oval pouring basin that is easy to produce but is not particularly successful at controlling melt flow pattern. Its small volume provides too short reaction time window for the operator to keep the liquid level stable. The pouring basin simply extends into the runners. The runners are a square grid that redirects the flow towards the castings. Its design is very primitive, without any reduction in cross section, to represent the bare minimum that serves the purpose. As the gates branch down from the runner, again without tapering, they provide relatively large vertical fall into the casting (200 mm). This unrestricted fall causes the melt to hit the bottom at a great velocity and hopefully create a significant splashing (see Fig. 2). As the pouring continues, the liquid level in the casting rises, reducing the height of the fall. This type of filling system creates a temperature gradient, placing the hottest section on the top of the casting, which is an advantage of the top gated system. Solidification of the casting is directional and occurs from the bottom-up, promoting better feeding.

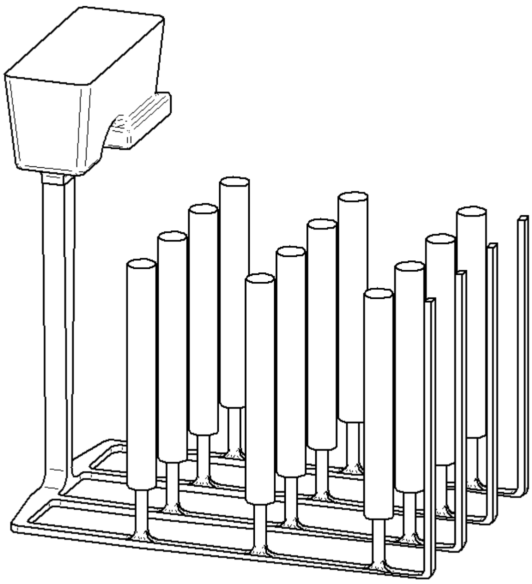

Figure 2. CAD drawing of the bottom gated system

The experimental design of top gated system is given in Fig. 2. The chosen geometry should provide a quiescent filling of the mould cavity, carefully avoiding air entrapment, high turbulence, and high melt velocity when entering the casting. The design begins with a carefully designed pouring basin. The well has an undercut, which reduces turbulence and splashing when the initial melt hits its bottom. Once the initial turbulence has settled, and the level of melt slowly rises in the filling well, it climbs over the rounded step, towards the sprue. The sprue is plugged with a ceramic stopper before the start of the pour to prevent rogue droplets and the very surface of the rising melt from entering. These contain the most oxides. Once the melt reaches about 60% of the pouring basin height the stopper is removed, and the melt starts flowing into the sprue, without turbulence, and containing a minimal number of oxides. The operator must keep pouring at a constant rate, so that the liquid level never drops too low, or overflows. This is achieved by making the pouring basin large enough to account for human reaction time, which is approximately one second. Increasing the pouring basin obviously reduces the effective yield of the casting, slightly increasing the cost of production due to recycling of the larger gating system. On the other hand, producing better castings, with fewer defective parts, and more consistent mechanical properties is economically beneficial, so the cost of the gating system should be net positive. The sprue is tapered, so that it follows the reducing cross section of the falling metal stream, preventing the stream from pulling air out of the mould and eroding the sand. The sprue and runner entrance are rounded, to reduce turbulence caused by the melt turning sharp corners. The runner branches into rows, which extend into the mould and connect to the gates. The cross section of the runner branches decreases after each gate, to accommodate the volume loss that goes into the casting. The runner ends in a vertical runner extension designed to catch the first melt that entered the gating system which contains the most oxides and possible inclusions. The vertical extension also provides backwards pressure into the runner, ensuring that melt velocity at the gates does not exceed critical value of 0.5 m/s, above which surface turbulence and splashing can occur. The gates are simple vertical tubes, extending from the runner into the casting. Their cross section is large enough to ensure the melt velocity is below above-mentioned critical value. The filling rate of the test pieces should be fast enough to prevent oxide laps from forming, so the part should be filled in the shortest time possible, while avoiding the creation of bifilms. This orientation of the filling system creates a thermal gradient in which the bottom of the casting is the hottest part, since the melt enters from there. This creates less optimal solidifying conditions, since there is no feeding of the part. Regardless of this, most of the part is going to be machined away, and its ends will only be used to hold onto while preforming tensile tests, so this should have minimal impact. Due to the small diameter of the part, and low shrinkage of the used alloy, no feeding of the castings is necessary.

The mould was made from quartz sand bonded with bentonite clay, with 5% moisture. The greensand mixture was carefully prepared and mixed, ensuring a homogenous mixture for both moulds, to remove mould variation interfering with the castings. The modelling set was a mixture of aluminium, and 3D printed parts. The mould was made using pneumatic, and hand tools. Fine parts of the gating system were closely inspected, the mould was cleaned of loose sand using compressed air, assembled, and covered to prevent loose sand or dust from entering before the pour. The ambient temperature at the time of pouring was around 30°C. The moulding was completed in around 1h before the pouring.

Table 1. Alloy chemical composition

Si (%)	**Fe (%)**	**Mg (%)**	**Cu (%)**	**Zn (%)**
7.55	1.39	1.34	0.97	0.71
Sn (%)	**Pb (%)**	**Mn (%)**	**Ti (%)**	**Al (%)**
0.50	0.26	0.21	0.05	Balance

The chemical composition of the used Al-Si alloy is given in Table 1. The alloy was heated to 700°C and held at the casting temperature for 4 hours. Temperature was measured before each pour. The slag was removed several times while holding and a final time immediately before pouring. Due to the low volume of the furnace, the two gating configurations could not be poured from the same batch. They were cast in two consecutive days, carefully replicating the same steps while melting, moulding, and pouring. After cooling, the moulds were broken, the gating systems were removed, and test pieces were machined to precise measurements shown in Fig. 3, and within dimension tolerances specified by [8].

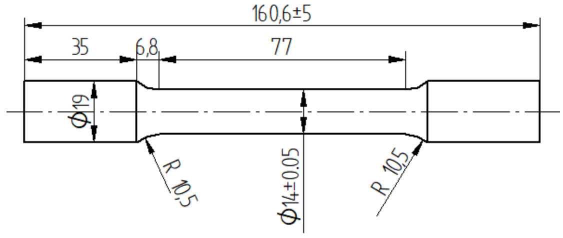

Figure 3. Technical drawing of a test piece

Machined test pieces were subjected to tensile strength testing on a VEB ZDM 5/91 Fmax 5kN at room temperature, according to the standard procedure [8]. During testing, some test pieces broke at the radius, making them invalid, so they were excluded from the results. A total of 14 top gated, and 8 bottom gated specimens were successfully tested.

3. NUMERICAL VERIFICATION OF GATING SYSTEMS

Both filling systems were examined using computer simulations in MAGMASOFT 5.4.1. The gating systems was modelled in Siemens Solid Edge 2023 and imported into MAGMASOFT 5.4.1. Corresponding materials were assigned to the parts of the assembly, and a mesh was generated. The density of the mesh was selected so that the smallest cross sections have at least 8×8 cells, and radii are well represented. High mesh quality is crucial in getting a good result of a numerical simulation. Parameters such as type of mould, mould temperature, initial melt temperature, and pouring rate were defined to match actual future experiment values. The simulation provided results that showed the melt behaviour, most importantly its velocity, and the progress of melt free surface during the mould filling. The differences in the filling systems are shown in Figs. 4 and 5. As intended, the top gated system has a major flaw, the slow movement of the melt in the runner, followed by a chaotic waterfall-like splashing into the part cavities.

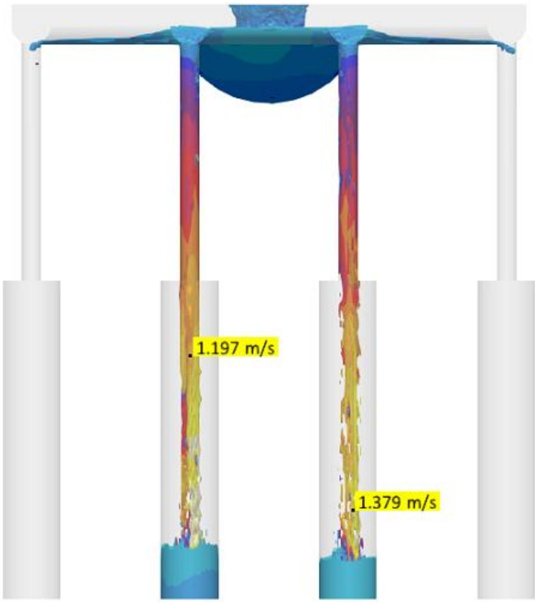

Figure 4. A side view of the top gated system, with velocity shown in colour (warmer colours represent higher velocity). Two points were picked to show melt velocity.

The melt velocity reaches 1.4 m/s and the stream breaks apart into individual droplets, before hitting the bottom of the mould. In contrast, the bottom gated system shows a gentle filling of the part, reaching only around 0.2 m/s when entering the test piece. The melt velocity in the sprue and runner is high, but this cannot be avoided due to the height of the castings. High melt velocity is not that detrimental when contained by a properly designed gating system and does not cause significant surface turbulence. The only turbulent part of flow in the bottom gated system is in the very beginning, while the sprue and runner are not yet completely filled with the melt. That is why the vertical runner extension is an important part of the gating system, since it catches the “dirty” melt that has the bifilms that were created while proper filling conditions were being established.

The simulation results can only be confirmed by actual experiments. They can be used only as a rough prediction of the actual test and cannot be trusted completely.

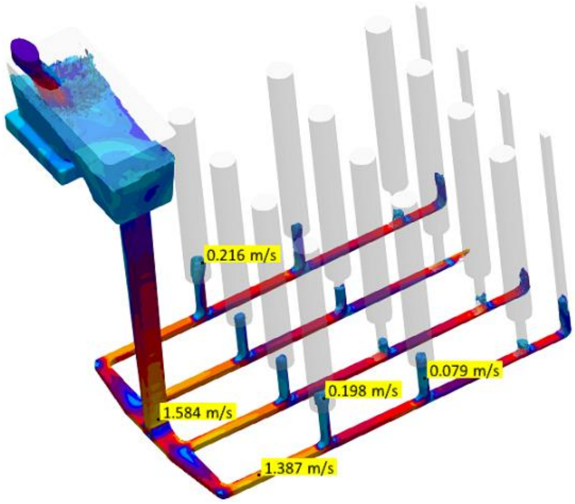

Figure 5. Isometric view of the bottom gated system, with velocity represented in colour. Several points were chosen to show velocity in certain areas.

4. RESULTS AND DISCUSSION

While pouring, several observations were made:

- Pouring time: the bottom gated system took less time to fill, around 4 seconds compared to 8, despite their similar mass (4,1 kg and 4.7 respectively). These pouring times align with the simulation results. The yield of both gating systems is similar: Top gated 46% and Bottom gated 41%, which further confirms that a much shorter pouring time can be achieved without compromising yield.
- Filling pattern: the top gated test pieces were filled one by one, with the pieces closest to the pouring cup being filled first. The splashing of the melt into the test pieces could be heard from the mould, and air from the cavity was

escaping through the gates. The bottom gated test pieces were all filled at the same time and the same rate. Due to the quality of the pouring basing, the bottom gated system was easier to pour.

- Casting difficulty: The top gated system was more difficult to pour, the pouring cup was close to overfilling, while the runners were half empty. This drastically extended the pouring time.

Due to a mistake which was later determined, the runner was 3D printed with 30% less height than required. This caused the last row of the bottom gated casting to be scrapped, since the melt froze in the runner before they were completely filled. These errors must be prevented in future research.

The results of tensile testing are shown in Table 2. Statistical analysis was performed using JMP Pro 14 (SAS Institute Inc.). Both top and bottom gated data was successfully tested for normality. Mean values, standard deviation, and 95% confidence intervals were calculated. The mean tensile strength and 95% confidence intervals of the specimens are shown in Fig. 6. The confidence intervals do not overlap, which shows a statistically significant difference in the results. A two tailed t-test was performed, and the resulting p-value was determined to be 0.00195. There is a statistically significant improvement in ultimate tensile strength of the bottom gated specimens, compared to top gated specimens.

Table 2. Tensile testing results

TG(MPa)	BG(MPa)
130.9	140.8
112.2	151.3
128.7	124.0
116.6	147.8
135.7	143.1
129.6	134.8
112.1	145.3
110.5	134.8
132.5	
127.4	
140.2	
135.1	
101.9	
128.7	

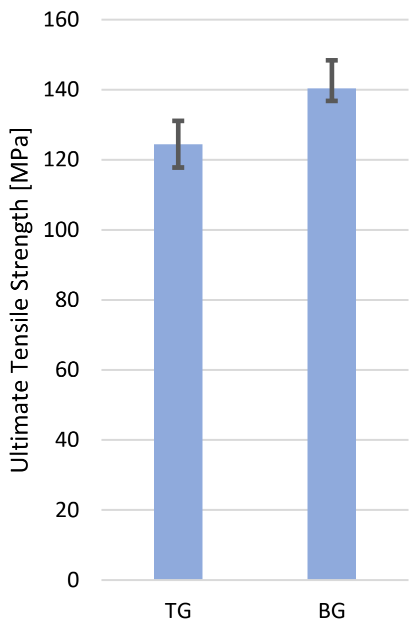

Figure 6. Comparison of top gated (TG) and bottom gated (BG) ultimate tensile strength with their respective confidence intervals. Eror bars represent 95% confidence intervals

This increase of mechanical properties is attributed to the lack of bifilms in the bottom gated test pieces.

Although mechanical properties could be affected by many factors, such as grain size, chemical composition, sand inclusions, microstructure, the experiment was designed to keep any variation of these factors to a minimum. Another important difference in the results is a narrower deviation of ultimate tensile strength in bottom gated specimens (8.8MPa compared to 11.5MPa).

Similar trends were reported by [7]. This also points to a lower presence of bifilms due to their impact on tensile strength, and result scatter. When subjected to tensile strain, bifilms act as initial cracks, and propagate cracks easier than sound test pieces. Depending on number of bifilms and their size, some test pieces fail at much lower strain, causing a greater scattering of results. In [4],[5], similar results were achieved on different Al-Si-Mg alloys, pointing to the detrimental effects of bifilms. In [6], a drop in

Ultimate tensile strength, and reliability in top gated castings was found in a Cu-Al alloy. In [7], entrained surface films were found to be responsible for much of the scatter in the mechanical properties and impaired the reliability of casting in an Al-Cu alloy.

5. CONCLUSION

- The bottom gated configuration proved to be easier to pour than top gated. A shorter pouring time, better filling pattern, and less splashing was observed in the bottom gated configuration.
- Tensile strength testing provided results which indicate that the bottom gated configuration yields statistically higher mechanical properties, with less spread.
- The experimental results point to the negative influence of bifilms on mechanical properties of castings.
- The experiment proved the methodology to be valid in determining detrimental effects of bifilms.
- Another iteration of the experiment, with both configurations being cast from the same batch, or connected in a branching gating system might provide even more convincing results on the negative effects of bifilms.
- Further studies, on aluminium alloys without magnesium are recommended.

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