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*Article*

# Numerical Simulation and Experimental Validation of Melt Flow in the Naturally Pressurized Gating System

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**Abstract:** The main problem during the production of castings from aluminium alloys is the presence of the reoxidation, which negatively affects the final casting quality. Liquid metal surface reacts with the surrounding atmosphere and oxide layer of $Al_2O_3$ is formed on its surface. The problem occurs when the oxide layer is entrained to the internal volume of the melt by turbulence and double oxide layers are formed, also known as "bifilms". Its formation is related to the melt velocity and gating system design. In paper, naturally pressurized gating system was calculated and designed. Effect of the filter media and vortex element on the melt velocity, amount of oxides, mechanical properties, and porosity were observed. Designs with 10 ppi and 20 ppi foam filters and vortex element were compared with design without filters to prove the positive (or negative) effect of filter media on melt velocity and thus on final casting quality. The melt velocity and amount of oxides were observed with the aid of simulation software. Mechanical properties, quantity of pores, bifilm index and EDX analysis were evaluated after experimental casts. It was proven that by using 20 ppi foam filter in combination with vortex element, the best results were achieved.

**Keywords:** foam filter; vortex element; melt velocity; double oxide layer; reoxidation process



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## 1. Introduction

Aluminium alloys are an important group of materials and their usage in the automotive and aerospace industry is still increasing. Nowadays, aluminium alloys enable to replace materials with higher weight and thus reduce fuel consumption and emissions. It is due to their suitable combination of mechanical properties and a wide range of usage, because aluminium alloys have high ratio of strength to weight, corrosion resistance, low melting point, good casting and thermal properties and especially light weight overall [1–5]. The use of aluminium alloys in the automotive and aerospace industry is related to increasing demands of casting quality. It leads to elimination as many casting defects as possible [6]. Possibility how to produce reliable castings is to follow the 10 rules for good castings by John Campbell [6,7].

The key issue in the production of castings from aluminium alloys is reoxidation process, which significantly affects the quality of liquid metal [6,8]. Surface of the aluminium alloy melt is exposed to atmosphere and the melt is easily oxidized to a few nanometres thick aluminium oxide layer on the melt surface due to its high oxygen affinity [9]. The result of reoxidation processes are double oxide layers which are formed in aluminium alloy castings primarily as a result of a combination of surface oxide formation and folding of these surface oxide films. Morphology of oxide films consists of different types of folds [10,11]. Oxide film, while remains on the surface of the melt, is not harmful. The problem occurs when the oxide film is submerged into the melt volume during filling process by turbulence and the oxide film is located in the final casting [3,9,11,12]. Mechanical properties of aluminium alloys castings and castings defects (mainly porosity) are affected by the presence of double oxide films [13,14].

One of the most important parameters during pouring which influences the reoxidation processes in the gating system is velocity of the liquid metal. According to Campbell's rules [7] it is very important that the liquid metal front should travel as slow as possible. There is an emphasis on melt velocity in the gate area being less than 0.5 $m \cdot s^{-1}$ for aluminium alloys. This critical melt velocity can be achieved easily because this value of melt velocity corresponds to fall of around 12.7 mm height. Higher melt velocity causes turbulence which increases the amount of entrained oxide layers from the surface into the melt volume [6,7].

Filter media placed in the gating system can remove the inclusions in the liquid metal by already known filtration mechanism what leads to a better mechanical properties and machinability [15–17]. Filter placement location is important parameter, because all inclusions formed after filter media can be trapped in the final casting and consequently decrease its quality [17,18]. However, it appears that a key purpose of filter media is a significant effect on the melt velocity, filling time, flow properties of the liquid metal and therefore reducing air entrainment. Type of filter media is important also, what will be subject to research during following experiments. In the research [17], using a flat filter or foam filter ensured the longest filling time. By using an extruded filter was observed the shortest filling time that was almost the same as without using the filter at all. Hwang et al. [19] examined the effect of ceramic foam filter and extruded filter on the flow properties via experiment of water modelling. The mentioned paper compared flow properties in the commonly used (unpressurized) gating system and adaptive gating system with filter added after the down sprue in the runner. The results showed, the runner's flow velocity can be reduced even by using 10 ppi filter. The 30 ppi foam filter showed the best results, the melt velocity decreased and splash jump height in the casting cavity decreased to an acceptable value. The performance of extruded filter was not optimal. The relationship between splash height and the kinetic energy of the liquid in the casting cavity and filter application has also been proven by water experiment and casting experiment in the research [20,21]. There was observed influence of the filter media in the gates area on the flow properties by the water experiment and via casting experiment was examined the porosity of final castings. The presence of filter had a significant role which prevented from the fountain like flow in the casting cavity and thus determined final quality of castings.

The ceramic foam filter effect on oxides elimination and mechanical properties was observed in the research [22]. With using the filter media, it was observed on the fracture surface of the samples a lower amount of oxide films compared to variant without a filter media (ductility increased also). In the paper [23] was observed behaviour of melt flow through ceramic filter placed horizontally in the runner via glass window in the mold. The melt was at first concentrated at the inlet side of the ceramic filter until the fluid pressure was sufficient to overcome the critical priming pressure. Subsequently, the molten metal was separated into multiple streams covered by an oxide layer and passed through the filter. Rather than preventing oxide film formation, the ceramic filter was a source of oxide film formation. On the other hand, the presence of the ceramic filter in the runner reduced surface turbulence in the runner after the filter and decreased the melt velocity by about 50%.

Pouring the liquid metal to the gating system is connected with air entrainment, which affects the final casting quality. Performance of filter and combination of filter and bubble trap depending on air entrainment in the gating system was examined with the aid of computational fluid dynamic software [24,25]. There was used high placed filter, low placed filter and low placed filter with the bubble trap according to Campbell [26]. The filters were placed vertically in the runner and compared with the gating system without the filter media. All variants with filter media were effective in reducing entrained air volume. The bubble trap also worked well, but only the complete simulations provided a comprehensive overview of this phenomenon. Filter placed in the runner ensured reduction of the melt velocity and more uniform priming of the runner behind the filter. However, it had not significant effect on more uniform filling of the mold cavity. It is in accordance with previous research.

Using a filter media can have a critical role for achieving good quality of castings. It is due to increasing flow characteristics of the liquid metal, reducing air entrainment and reducing the melt velocity which leads to calm filling of the mold cavity.

The purpose of this paper is to present design, which reduce reoxidation as much as possible because reoxidation processes cannot be completely removed in the casting process. To achieve this, the naturally pressurized gating systems was designed and calculated. This type of gating system is still not commonly used for aluminium alloys castings due to the high melt velocity. Therefore, the work deals with the effectiveness of foam filters and vortex element at the end of runner to reduce the melt velocity in the naturally pressurized gating system.

## 2. Materials and Experimental Methods

For the experimental purpose, effectiveness of foam filter media and combination of foam filter with runner modification by vortex element in the naturally pressurized gating system were evaluated by simulations and experimental casts. Typical non-pressurized gating system for aluminium casting was replaced by naturally pressurized gating system, which application for aluminium alloy castings is still rare due to high melt velocity. The gating system was designed and calculated as a naturally pressurized with cross-sectional ratio of gating system 1:1:1 ($A_{sprue}$:$A_{runner}$:$A_{gate}$). Naturally pressurized gating system was used due to suppression of reoxidation during pouring. The liquid metal is in direct contact with the mold walls during filling and thus turbulence formation is eliminated. However, high melt velocity is expected. For experiments was designed casting with different thickness and exact dimensions are according to Figure 1.

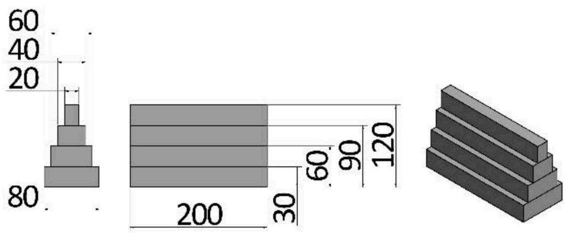


**Figure 1.** Casting design.

For the evaluation of foam filter and vortex element effect, three constructions of gating system were designed. The first alternative was design of naturally pressurized gating system without filter media or runner modification (Figure 2). For foam filter effect evaluation was designed naturally pressurized gating system with horizontally placed foam filter in the gate area (Figure 3), at this construction design were evaluated two types of foam filter (10 ppi and 20 ppi). Figure 4 shows design with 20 ppi foam filter and extension of the runner by vortex element. The first part of analysis evaluates the influence of foam filter and vortex element by the aid of numerical simulation software ProCAST. For the experimental work, the simulation boundary conditions were adapted to the conditions of real experimental casting. As an experimental material was used aluminium alloy A356 without any modification and grain refinement. Chemical composition of used experimental material is shown in Table 1. Experimental aluminium alloy was melted in the electric resistance furnace without degassing and refining process. The casting temperature was 720 °C. The melt temperature was checked by K type thermocouple before casting process. Casts were poured by gravity method to the resin bonded sand mold preheated to 150 °C. Pouring height was 150 mm and ambient temperature was 20 °C. After experimental casting, the mechanical properties (tensile strength and elongation), porosity quantification, bifilm index and EDX analysis were evaluated. Three specimens for each design were evaluated.

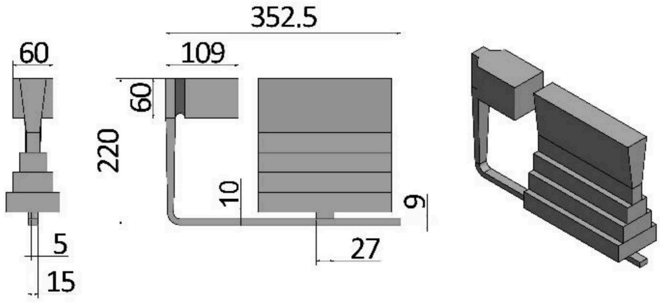


**Figure 2.** Naturally pressurized gating system without foam filter.

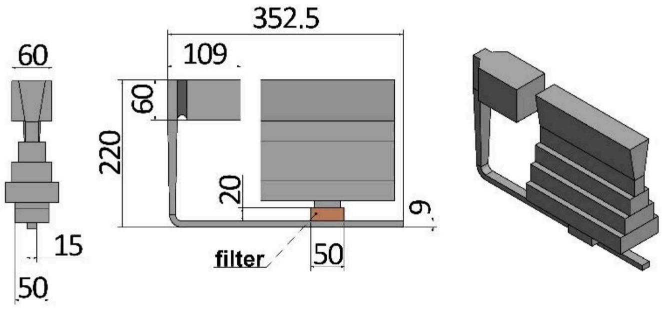


**Figure 3.** Naturally pressurized gating system with 10 and 20 ppi foam filter.

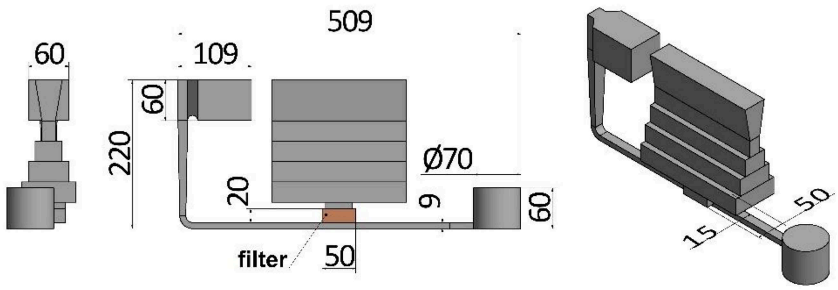


**Figure 4.** Naturally pressurized gating system with 20 ppi foam filter and vortex element.

**Table 1.** Chemical composition of aluminium alloy A356.

| Element | Si | Cu | Mg | Ni | Fe | Mn | Al | Ti | Sr |
|---|---|---|---|---|---|---|---|---|---|
| [wt. %] | 7.01 | 0.001 | 0.308 | 0.003 | 0.097 | 0.018 | 91.89 | 0.122 | 0.021 |

Tensile strength evaluation was performed on the machine Tira TEST 2300. Porosity quantification and bifilm index were evaluated by QuickPHOTO INDUSTRIAL 3.1 software. SEM analysis was used for pores observation and EDX analysis provided chemical composition of inner surface of pores. Specimens were wet grounded, for polishing was used diamond paste and silica slurry. For pores observation was used VEGA LMU II scanning electron microscope with EDX analyser Brucket Quantax for EDX analysis.

## 3. Numerical Simulation Results and Discussion

Results of melt velocity in the gate area and amount of oxides in the final casting were evaluated. Achieved results of designed gating systems were discussed and compared with each other. Table 2 provides the simulation parameters.

**Table 2.** ProCAST parameters.

| Casting parameters | Based on real casts conditions |
| --- | --- |
| 2D element size | 2 mm |
| Number of generated 2D elements | 140,000 |
| Number of 3D tetra elements generated | 1,332,000 |
| Method of filling | Gravity sand casting |
| Heat-transfer coefficient | AlSi7Mg0.3/Resin bonded sand interface |
| Stop Criterion | Final temperature 538 °C reached in all volumes |
| Temperature results storage | 1 (each step) |
| Velocity results storage | 1 (each step) |
| Turbulence model | Standard k-epsilon model |

### *3.1. Naturally Pressurized Gating System without Filter Media*

Construction of naturally pressurized gating system without filter media was designed as a reference gating system to observe foam filter and vortex element efficiency, because critical melt velocity flowing through the gate was expected. According to Figure 5, the critical melt velocity (above 0.5 $m \cdot s^{-1}$ at the entrance the mold cavity) in the gate area was reached. Reason of critical melt velocity passed gate is due to absence of mechanism to reduce the flow, because there is no cross-sectional extension of any part of gating system. Energy of the melt at the end of the runner was transferred to the gate area. Unreduced melt velocity caused high melt jump height in the mold cavity. It resulted in extensive reoxidation due to falling of melt stream from high height on the melt surface. Falling melt caused entraining double oxide layers into the melt volume. The amount of oxides in the final casting was affected by velocity of liquid metal. In the naturally pressurized gating system without filter media, velocity of the liquid metal was not reduced and the large amount of oxides was reached. In all simulations of amount of oxides, cm**2 unit represent $cm^2$.

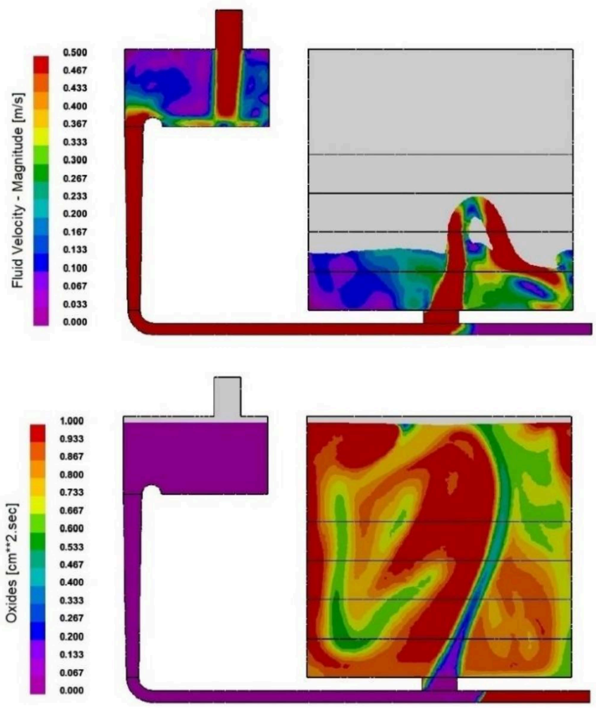


**Figure 5.** Simulations of the melt velocity and amount of oxides in the naturally pressurized gating system without foam filter.

According to Campbell [13], the melt velocity is directly related with the amount of oxides. Naturally pressurized gating system without mechanism to reduce the melt velocity is not suitable because benefits of this system in terms of reduction of reoxidation processes during filling the system are eliminated by high melt velocity.

### 3.2. Naturally Pressurized Gating System with 10 and 20 ppi Foam Filter

The simulation results of foam filter effect in the naturally pressurized gating system showed that foam filter placed horizontally in the gate area ensured significant reduction of melt velocity entering the mold cavity. As illustrated in Figure 6, the 10 ppi foam filter ensured reduction of the melt velocity at the entrance the mold cavity below 0.5 m·s$^{-1}$, which was associated with calmer filling of the mold cavity without high melt jump height. It resulted in a significant elimination of a large amount of oxides in the casting compared to the gating design without filter media. Foam filter density also influenced melt velocity and splashes rate. By using the 20 ppi foam filter, the entrance melt velocity was suppressed below 0.35 m·s$^{-1}$ and amount of oxides in the final casting was also reduced (Figure 7). With increasing ppi of foam filter the melt velocity is slower and it causes suppression of turbulence during filling the mold cavity. Because of turbulence suppression, the amount of oxides reduction was occurred in the design with 20 ppi foam filter compared to design with 10 ppi foam filter.

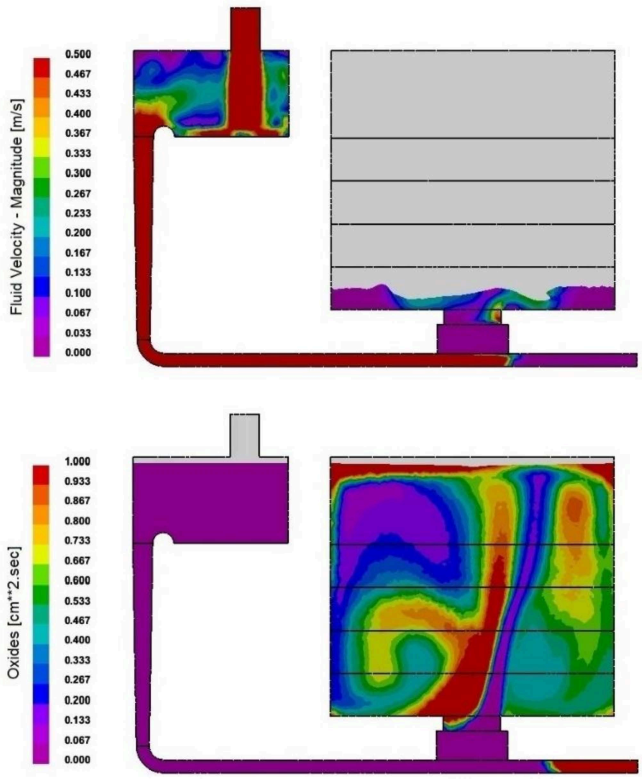


**Figure 6.** Simulations of the melt velocity and amount of oxides in the naturally pressurized gating system with 10 ppi foam filter.

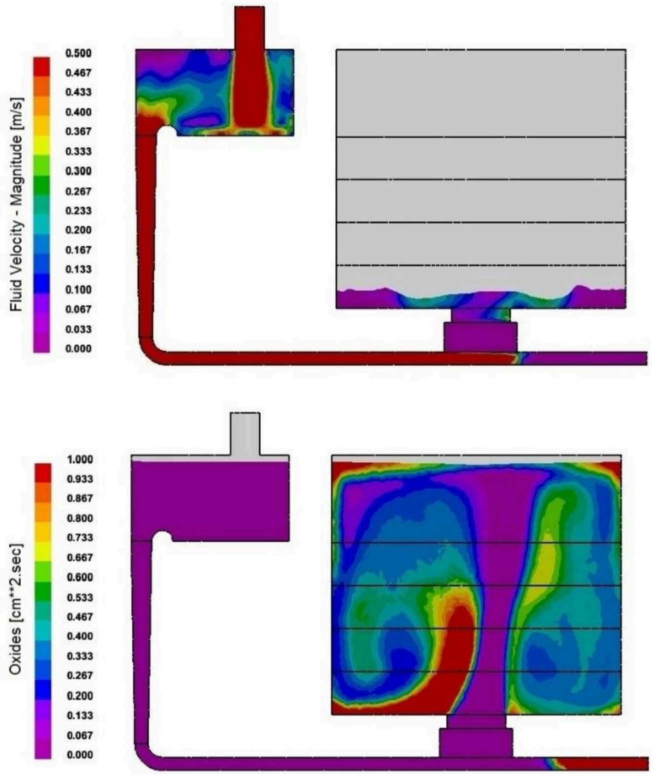


**Figure 7.** Simulations of the melt velocity and amount of oxides in the naturally pressurized gating system with 20 ppi foam filter.

### *3.3. Naturally Pressurized Gating System with Vortex Element and 20 ppi Foam Filter*

The best results of the melt velocity reduction at the entrance the mold cavity were obtained in the design of naturally pressurized gating system with horizontally placed 20 ppi foam filter and vortex element. Vortex element with circular cross-section was connected with the end of runner with rectangular cross-section. Volume of vortex element was designed based on the air entrainment simulations in the sprue. According to air entrained volume in the sprue, the vortex element volume and thus diameter and height of vortex element were determined. As shown in Figure 8, the front of the liquid metal was directed to the vortex element at the end of the runner. In this part of the gating system, the melt velocity was significantly reduced. Reduction of the melt velocity was ensured by extension of vortex element cross-section. The entrance of melt velocity at the gates was suppressed below 0.3 $m \cdot s^{-1}$. The gating design with vortex element in combination with 20 ppi foam filter ensured calm filling of the mold cavity without high melt jump height. It was provided by vortex element at the end of runner, where the melt flow energy was captured. When the liquid metal was in direct contact with the wall of vortex element, the melt flow was directed to tangential swirling motion. It ensured that the mold cavity avoided splashes formation and thus the amount of oxides in the final casting was reduced to low level against gating designs without modification of the runner. Naturally pressurized gating system with vortex element appeared to be a suitable way to reduce the amount of oxides in the final casting. A disadvantage of this system is metal yield decreasing about 12%.

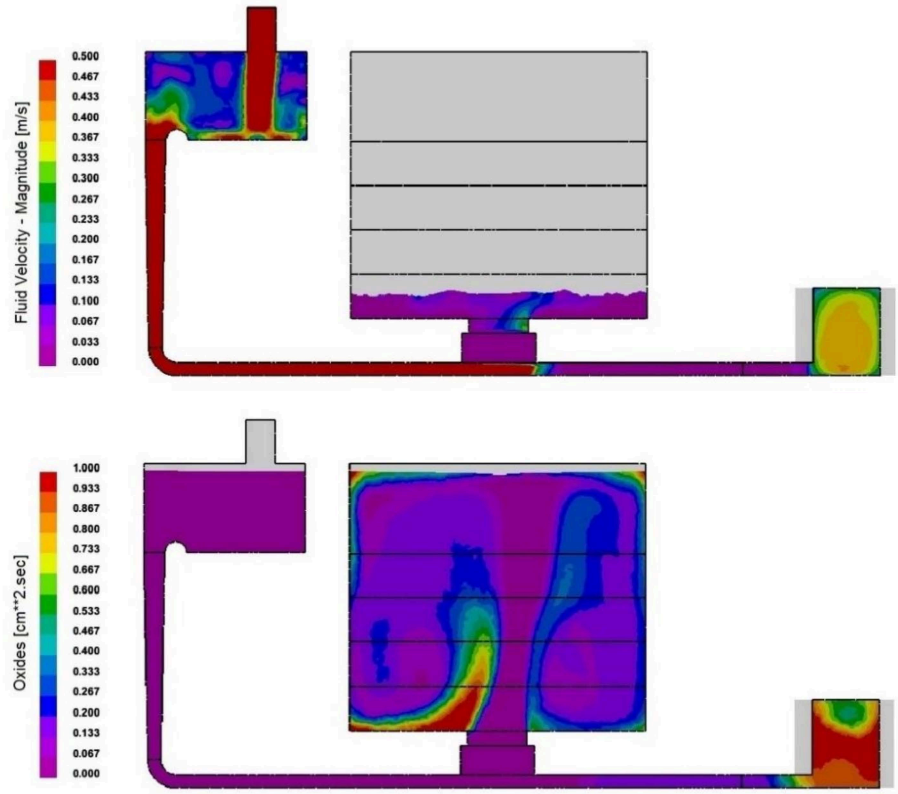


**Figure 8.** Simulations of the melt velocity and amount of oxides in the naturally pressurized gating system with 20 ppi foam filter and vortex element.

## 4. Experimental Casting Results and Discussion

Experimental casts were focused on the filter media and vortex element influence on the mechanical properties and porosity of final casting. Effect on the tensile strength and elongation were observed and porosity was quantified.

### *4.1. Foam Filter and Vortex Element Influence on the Mechanical Properties*

For each gating system design, the samples were taken from castings for a tensile test. Three samples were taken from each casting and average values of tensile strength were determined. Tensile tests were performed on the Tira Test 2300 testing device, also average elongation was determined for each design of gating system.

Based on the numerical simulations, the results obtained from the mechanical properties evaluation deduced that the amount of oxides influenced tensile strength and elongation. Increasing amount of oxides in the casting had negative effect on the mechanical properties and thus final casting quality. The lowest elongation and tensile strength were achieved in the design without filter media as was expected. Gating system design with 10 ppi foam filter suppressed the melt velocity at the entrance the mold cavity, amount of oxides was reduced and mechanical properties in this design were increased. Tensile strength and elongation raised about 5%. Increasing density of foam filter ensured a raising of tensile strength by 12% and elongation by 8%. The best results were obtained in the gating system design with 20 ppi foam filter and modified runner by vortex element. In this design, tensile strength was raised by 20% and elongation by 14%. Results of average tensile strength are illustrated in Figure 9 and average elongation in Figure 10. Based on results of tensile strength and elongation evaluation, it can be stated that foam filter with runner modification by vortex element in the naturally pressurized gating system proved the positive effect on the final quality of casting.

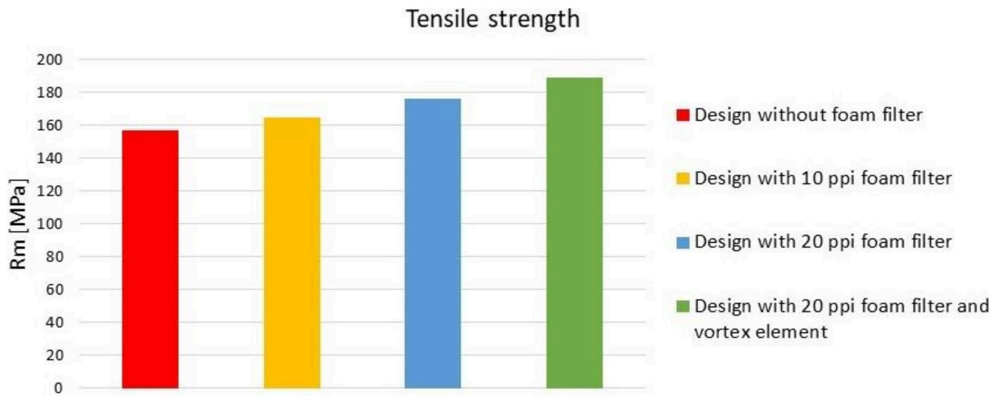


**Figure 9.** Results of tensile strength evaluation.

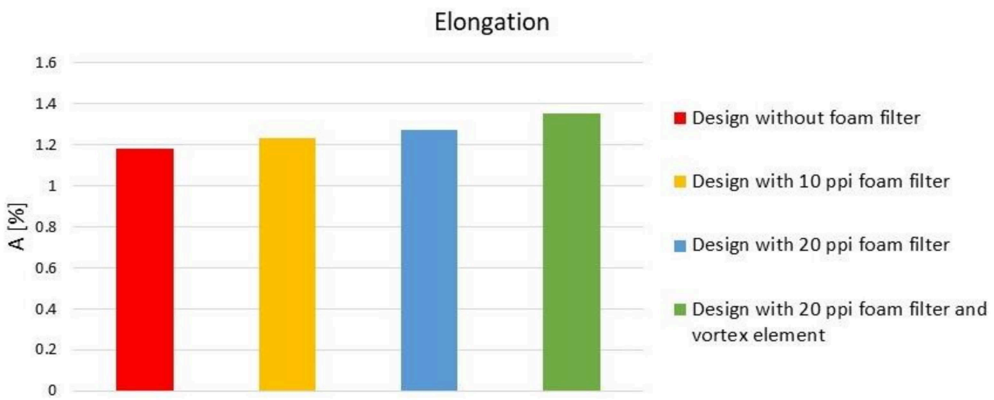


**Figure 10.** Results of elongation evaluation.

### *4.2. Foam Filter and Vortex Element Influence on the Porosity*

The porosity was observed on specimens taken from the castings at the location according to Figure 11. This location was based on simulations, where it was assumed a large rate of changes of oxide occurrence. This could be convenient from the point of view of quantitative porosity evaluation.

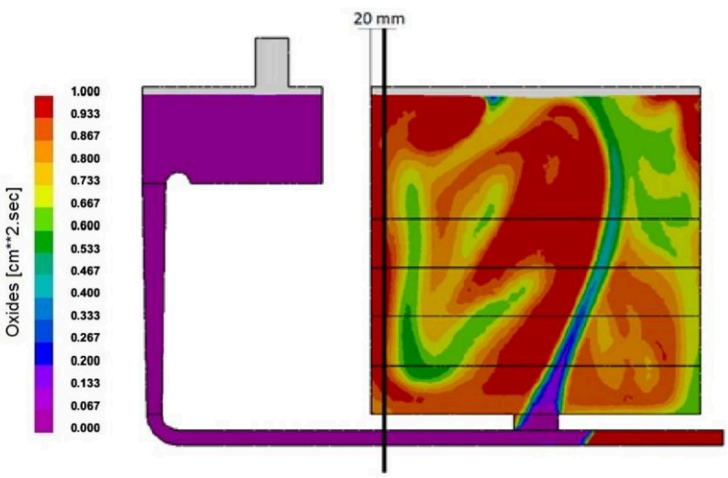


**Figure 11.** Location of porosity observation.

The data of porosity were obtained by QuickPHOTO INDUSTRIAL software where via graphic filters were all pores selected and summarized. The highest rate of porosity was achieved in the gating system design without foam filter (Figure 12a). It is caused by large amount of oxides, because without mechanism to reduce melt velocity the mold cavity was exposed to high splashes height. By using 10 ppi foam filter the porosity rate declined (Figure 12b). Increasing density of foam filter ensured lower rate of porosity (Figure 12c). In the gating system design with foam filters, rate of porosity declined, and pores size decreased also. Foam filters ensured reduction of pores rate by 35–45% compared to gating system without foam filter. The results of the porosity observation manifested that vortex element in the naturally pressurized gating system significantly suppressed the porosity rate (Figure 12d). It was assumed that it is due to the lowest amount of entrained double oxide layers in the final casting. Vortex element in combination with foam filter reduced porosity by 75%. Taken together, these results suggest that there is an association between amount of entrained double oxide layers and quantity of pores. Average porosity rate of three specimens of each design is represented in Figure 13.

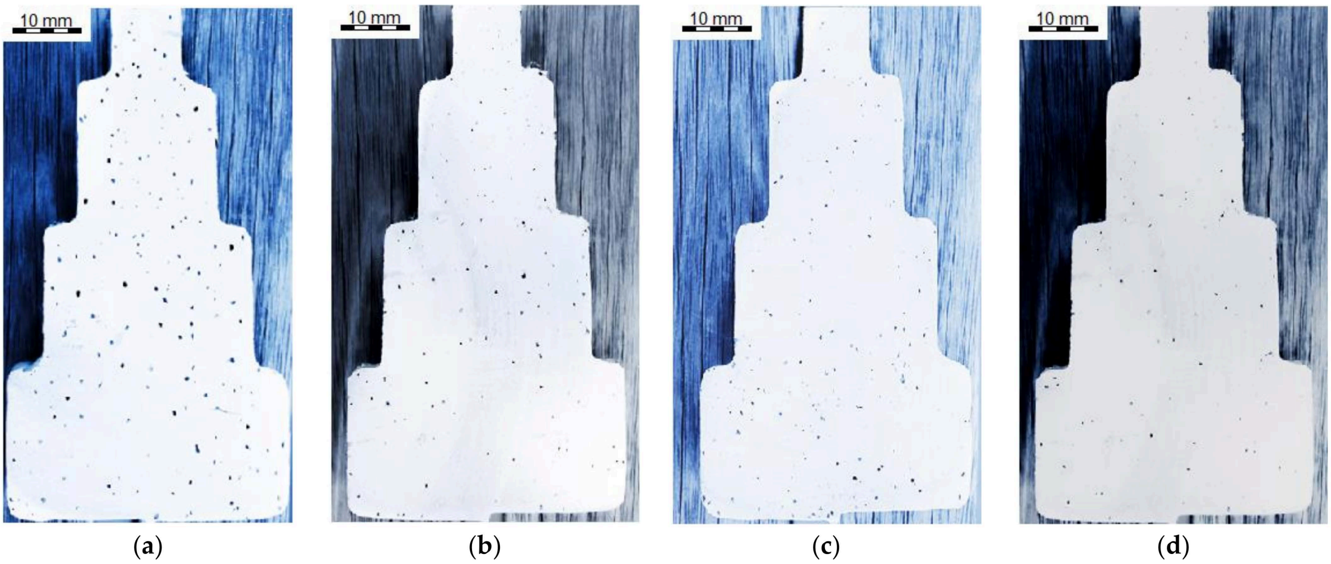


**Figure 12.** Porosity in specimens: (**a**) Design without foam filter; (**b**) Design with 10 ppi foam filter; (**c**) Design with 20 ppi foam filter; (**d**) Design with 20 ppi foam filter and vortex element.

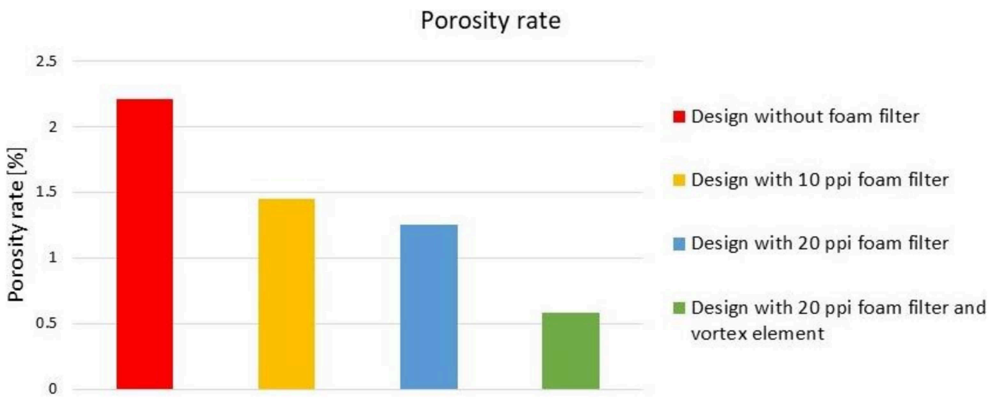


**Figure 13.** Results of porosity evaluation.

After pores quantification, maximal length of each pore was measured to determine bifilm index according to Equation (1). Bifilm index is determined as the sum of maximum lengths of pores. QuickPHOTO INDUSTRIAL software was used for length measurement of pores, as illustrated in Figure 14. Results of bifilm index corresponded with porosity rate. By using foam filter, bifilm index declined and the best results achieved the design with 20 ppi foam filter and vortex element as expected. Figure 15 showed the results of bifilm index observation. Measurement of maximum pore length also showed that in the designs with foam filter this parameter decreased. In the design without filter, maximum pore length was 4604 µm, while in the design with 20 ppi foam filter and vortex element maximum pore length was 2189 µm. By using 10 ppi and 20 ppi foam filter, maximum reached length of pore was 2843 µm respectively 2444 µm.

Bifilm index equation:

$$BI = \sum L_{max} \quad (1)$$

**Figure 14.** Bifilm index examination on the sample with 20 ppi foam filter and vortex element.

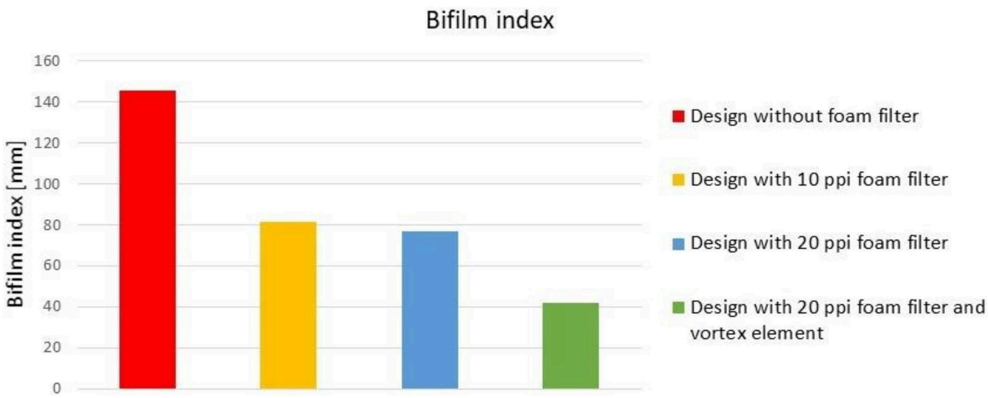


**Figure 15.** Results of bifilm index evaluation.

The relationship between pores and double oxide layers was observed via SEM-EDX analysis. SEM images showed inner surface of pore. Folds occurred on the inner surface of the pore, which is a typical morphology of the folded bifilm oxide layer. The oxide layer presence is also indicated by EDX analysis, which detected the higher presence of oxygen on inner pore surface, as shown in Figure 16. It corresponded with the work [27], where authors claimed that the pore formation is related to entrained double oxide layer and double oxide layer is initiator of pore formation.

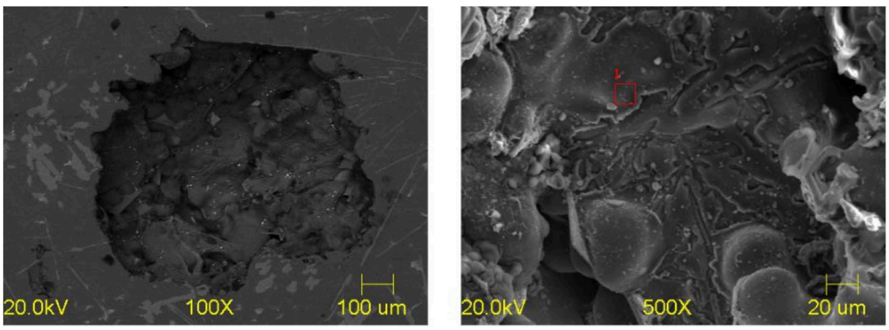


**Figure 16.** *Cont.*

| Elt. | Intensity | Error (c/s) | Gauss 2-sig | Atomic Fit | Conc % | |
|---|---|---|---|---|---|---|
| O | 1.92 | 0.506 | 1.54 | 27.603 | 18.324 | wt.% |
| Al | 34.36 | 2.140 | 2.77 | 58.690 | 65.703 | wt.% |
| Si | 3.76 | 0.708 | 0.50 | 13.707 | 15.973 | wt.% |
| | | | | 100.000 | 100.000 | wt.% |

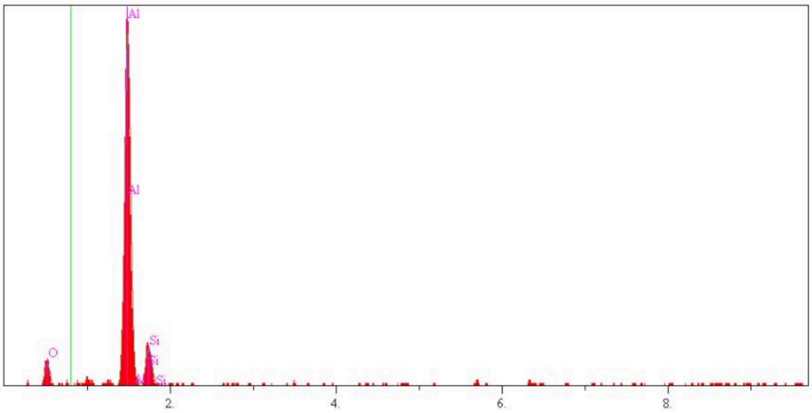


**Figure 16.** SEM and EDX analysis of pore inner surface.

## 5. Conclusions

The paper dealt with the naturally pressurized gating system design for the aluminium casting process. High melt velocity was expected at the entrance the mold cavity. Therefore, the purpose of this work was to suggest a way to reduce the melt velocity and thus to fill the mold cavity without turbulence. Reduction of the melt velocity in the naturally pressurized gating system was examined by using foam filters and vortex element and its influence on the final casting quality was observed. This work provided innovative methods how to produce reliable aluminium alloy castings. Based on the results of the simulation observation and experimental casting, it can be stated:

- The simulations and experimental casting confirmed the effectiveness of the foam filter and vortex element on the melt velocity which corresponds with previous works [19,28,29].
- Reduction of the melt velocity via foam filter is associated with significant reduction of oxides amount in the casting.
- The foam filter and vortex element had a positive effect on mechanical properties of castings.
- Increasing of foam filter density was related with reduction of the melt velocity, amount of oxides and thus mechanical properties.
- The relationship between the melt velocity and final casting quality was proved by experimental casting.
- SEM-EDX analysis showed presence of oxide layer on the inner surface of pores. It is consistent with works [27,30].
- Vortex element application decreased metal yield about 12% compared to the reference gating system. However, it can be negligible in the case of responsible casting because was proven that the best results of tensile strength, elongation and porosity rate were achieved.
- In the future work, the gate design will be modified to ensure decrease of air entrainment and thus pore formation. It will be investigated the effect of tangential filter gate and trident gate.

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