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THEORETICAL AND EXPERIMENTAL INVESTIGATION OF THE EFFECT OF DESIGN CRITERIA ON POROSITY IN HPDC OF AlSi9Cu3(Fe) ALLOY

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Highlights

- Number of runner and airflow, switch point location and second phase speed value was determined by a commercial programme in HPDC.
- Experimental studies were carried out with a die set manufactured in accordance with the simulation results.
- The porosity level was found to be very low and acceptable according to the standards.

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Abstract

The aim of present study is to prevent the rejection of parts because of the porosity during the high pressure die casting (HPDC) process. Die design was carried out for the production of the engine connection part for automotive industry with HPDC. Process parameters taken into consideration for study are number of runner and airflow, switch point location and second phase speed value. Number of aiflows and runner was determined acoording to simulations. In order to determine the number of runners, simulations were made by considering 5 basic parameters and care was taken not to turbulent material flow in the mold. Then, the location of the switch point and the second phase speed were determined by simulation studies. After the simulation studies were completed, the molds were manufactured. Then, HPDC process was carried out using AlSi9Cu3(Fe) alloy. The casted parts were analyzed by means of porosity using computed tomography (CT) and optical microscope (OM). The porosity level was found to be very low and acceptable according to the standards.

AlSi9Cu3(Fe) ALAŞIMININ YÜKSEK BASINÇLI DÖKÜMÜNDE TASARIM KRİTERLERİNİN POROZİTEYE ETKİSİNİN TEORİK VE DENEYSEL OLARAK ARAŞTIRILMASI

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Öz

Bu çalışmanın amacı, yüksek basınçlı döküm (HPDC) prosesiyle elde edilen parçaların porozite nedeniyle reddedilmesini önlemektir. Kalıp tasarımı otomotiv endüstrisinde kullanılan bir motor bağlantı parçasının HPDC ile üretimi için yapılmıştır. Çalışma için dikkate alınan proses parametreleri, yolluk ve hava cebi sayısı, sviç noktası konumu ve ikinci faz hız değeridir. Hava cebi ve yolluk sayısı simülasyonlara göre belirlenmiştir. Yolluk sayısını belirlemek için 5 temel parametre dikkate alınarak simülasyonlar yapılmış ve kalıpta türbülanslı malzeme akışı olmamasına özen gösterilmiştir. Daha sonra simülasyon çalışmaları ile sviç noktasının konumu ve ikinci faz hızı belirlenmiştir. Simülasyon çalışmaları tamamlandıktan sonra kalıplar işlenmiştir. Daha sonra AlSi9Cu3(Fe) alaşımı kullanılarak basınçlı döküm işlemi gerçekleştirilmiştir. Üretilen parçalarda, bilgisayarlı tomografi (CT) ve optik mikroskop (OM) kullanılarak gözeneklilik kontrolü yapılmıştır. Porozite seviyesi standartlara göre çok düşük ve kabul edilebilir mertebede bulunmuştur.

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1. Introduction

Doehler produced parts by applying the high-pressure casting method to aluminum alloys in 1915, and the use of HPDC has become a widespread industry. In the high pressure die casting method for the alloys such as aluminium, the most important component of the design is the injection die. The injection die is designed and produced according to different capacity injection machines depending on the part to be produced. The production life of the dies may vary and can be up to 100,000-150,000 parts.

The high pressure casting (HPDC) process is a very useful and preferred manufacturing method for mass production of casting alloys with high dimensional accuracy, good surface quality and great productivity. Aluminium, magnesium, copper and zink parts can easily be produced by this method. The design and layout of casting systems (gate and runner, overflows, vents) are vital factors influencing melt flow properties during HPDC die filling. Correct configuration of gate and runner systems and optimum casting parameters can lead to casting components with improved mechanical properties and casting consistency. In order to inject molten metal into the die, mainly two different systems may be used as; hot chamber system and cold chamber system. Karthik et al. (2020) experimentally showed the optimization of high pressure die casting process parameters such as melt temperature, die preheat temperature and compression pressure load. The researchers also determined the most important process parameter affecting hardness and density. Zhou et al. (2019) designed a new runner and showed that the mechanical properties of the cast alloys produced with the optimized runner system increased obviously. Ultimate tensile strength and elongation for HPDC aluminum alloys has been improved by Gunasegeram et al. (2013) by optimization of runner design and increasing the piston velocity. Kwon and Kwon (2019) studied the design of HPDC gating systems using CAE method and predicted the cast defects accordingly. Cho and Kim (2014) investigated the effects of cooling rate on the solidification behaviour of two aluminium alloys during high pressure die casting (HPDC). They also used MAGMA simulation in order to compare experimental results with the software. Gökçil (2019) performed a doctoral study on optimum die design and determination of casting process parameters with the help of Magmasoft software during the production of a commercial product by high pressure casting method. Thoma et al performed an experimental study. In the mentioned study, the tensile specimens obtained from the parts produced by the HPDC method were modelled in numerical casting simulation according to their geometry and position in the casting part. It has been shown that the mechanical properties of the specimens are compatible with the simulation results of a commercial casting simulation software called Flow-3D. Patel et al. (2014) studied the effect of process parameters such as die temperature, pouring temperature and compression pressure on the surface roughness and density of the LM20 alloy. Balikai et al. (2018) carried out studied the optimization of the process parameters of the HPDC process for the ADC 12 aluminum alloy. Nagasankar et al. (2018) investigated the reduction of vents in the HPDC machine by changing the levels in the process factor high-speed change position. In their study, the authors also changed the design of the die by changing the inlet direction to improve the model of the molten metal flow. They revealed that with the improved die design, the rejection rate decreased from 20% to 8.9%.

On the other hand, depending on the process parameters during injection, turbulent melt flow causes entrapped air and gas porosity, which degrades the mechanical properties. There are two types of porosity formation in the HPDC process. The first of these occurs as a result of gas entrapment in the die filling at high speed. In the second, they are pores caused by shrinkage during solidification (Li et al., 2016). Some investigators have shown that the application of vacuum in HPDC processes significantly reduces the amount of entrapped gas during the filling (Niu et al., 2000; Li et al., 2016; Hu et al., 2017). Tsoukalas (2003) investigated the effect of die casting machine parameters (piston speed, condensation pressure, die cavity filling time) on porosity formation in casting components. In the mentioned study, it has been revealed that the optimum selection of casting parameters leads to the optimum porosity value in the finished part. Dumanic et al. (2021) simulated high-pressure die casting of A356 semi-solid aluminium alloy by using three input parameters such as liquid fraction of slurry, plunger velocity at 2nd phase and die geometry. Optimal process parameters have been obtained the Taguchi-based ‘grey relational analysis’ approach in order to prevent microporosity. Lu et al. (2009) found that the initiation and expansion of the fatigue crack were highly sensitive to geometry, size and distribution of the porosity. Teng et al. (2009) investigated the relationship between ductility and the largest pore size on the fracture surface in the casting of Al–9Si–0.3 Mg alloy with HPDC. In his thesis, Kenar (2019) studied the valve (gas discharge) die designs of two different automotive components produced from AlSi12Cu1Fe and AlSi10MgFe alloys by high pressure casting process and examined the results. Studies have focused on cold bonding, blister and porosity casting defects. In his thesis, Doğan (2019) investigated the comparative performance of three different degassing systems with different designs on two different aluminum alloy parts (AlSi9Cu3-Fe, AlSi10Mg-Fe) in a high pressure die casting system. For the quality analysis of the cast parts produced, porosity regions, porosity ratios and distributions were determined by X-Ray radioscopy, computed tomography (CT).

In this study, a die design for the production of the engine connection part of an automotive with HPDC was made for the company headquartered in Europe. This connection part is expected to have high strength. There should be no breakage in this part, which has a critical task. For this reason, the porosity level of the part should be very low and there should never be a shrinkage gap. 5 main parameters were considered for design of runner and then switch point location and plunger speed were determined by a commercial CAD programme called NOVAFLOW&SOLID. AlSi9Cu3(Fe) alloy was chosen as cast material. Porosity analyzes were carried out by computed tomography optical microscope.

2. Determination of the Design Parameters According to Simulation

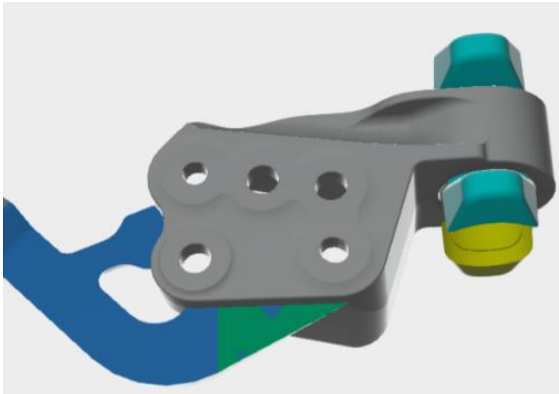
2.1. Airflow Design

The primary task of the airflow is to expel the air and the gases inside the die during the injection of the product. At the design stage of the die, the airflow should be placed in the thickest region of the product and the furthest away from the runner. An important point to be followed in the simulation is that the airflow should not be filled before the product. Otherwise, porosity will be occured in the part. In the presented study, a total of four-airflows were designed for the part to be produced and placed in the appropriate place of the die.

2.2. Runner Design and Detection of Number of Runners

There are certain parameters for the runner design. The most important of these parameters is the calculation of the cross-sectional area. While calculating the cross-sectional area, it starts from the area of the entry region and continues until the biscuit area. After the calculating of the cross-sectional area, the runner design is performed. Too many indentations, curves, sharp corners are not preferred in the runner design. The flow should always be laminar, and there should be no loss of energy. In this study, the runner design of the part was designed considering these criteria.

Generally, it is not preferred to use more than single runner when designing runners in injection dies. However, since the part to be produced in the presented study is relatively large and thick, two-runners can also be preferred. In this regard, two different designs including one runner and two-runners were considered for the injection of the part to be manufactured and shown in Figure 1. The simulation results for both runner types are analyzed by considering different parameters given below and the most suitable design in terms of surface quality and porosity was determined.



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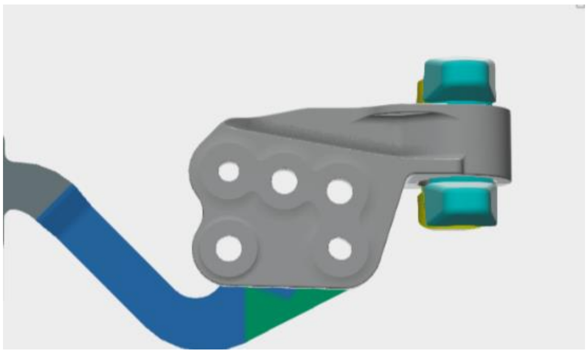

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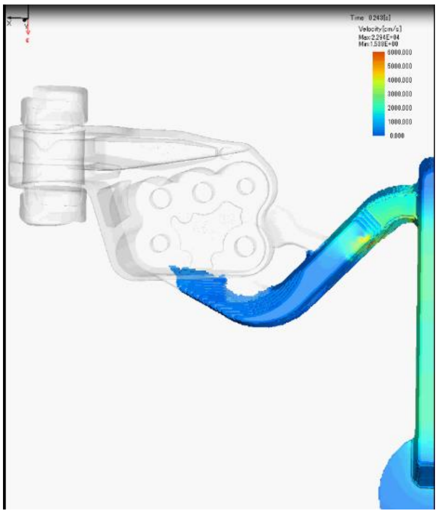
Figure 1. a) Design of two-runner for the part b) Design of single runner for the part

2.2.1. Metal Flow into the Die

Metal flow simulation was performed under nominal conditions and the results are shown in Figure 2. Figure 2.a shows the simulation results of the design with two-runners. As it can be seen, while aluminum alloy will be filled into the part from the large runner, aluminum alloy has not yet come to the other runner inlet. This will disrupt the laminar flow conditions in the die and increase the possibility of porosity. Because after the material flow from the first runner, the entry of material from another runner creates turbulence. As can be seen in Figure 2.b, there is no such danger in a single runner.



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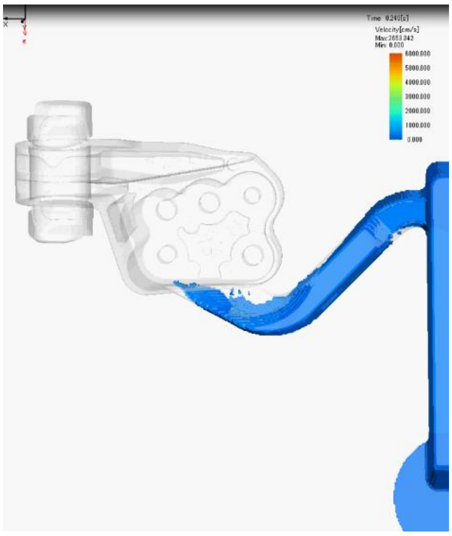

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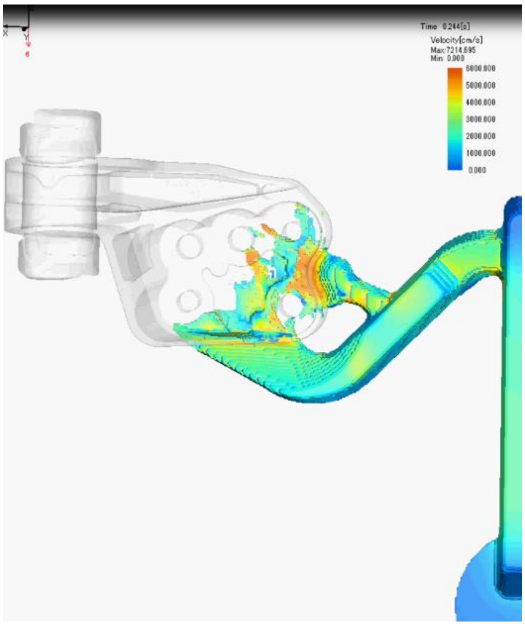
Figure 2. Metal flow condition results a) Metal flow simulation of two-runner design b) Metal flow simulation of single runner design

2.2.2. Sticking over the Pin

Due to the original geometry of the part, there is a pin on the part. This pin is very close to the smaller runner in the two-runner system, depending on the design, as shown in Figure 3.a. When the simulation is examined in detail, the molten aluminum hits the pin at high speed. Therefore, the surface quality of the part will be deteriorated and the part will be diccarded during the quality control stage. In the single runner design shown in Figure 3.b, the injected aluminum alloy fills the die without hitting the pin and laminar flow takes place in the die.



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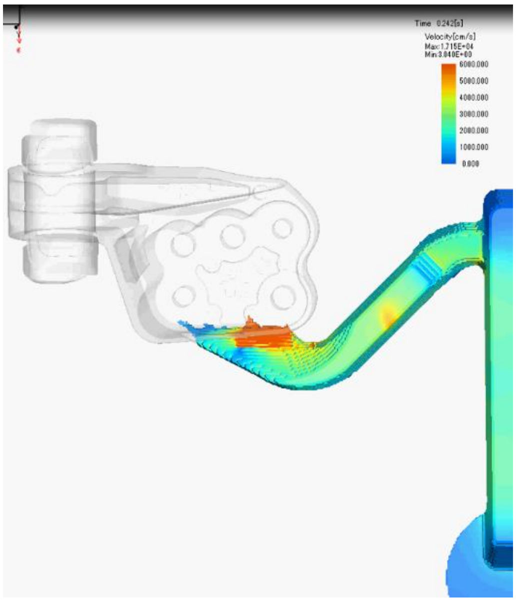

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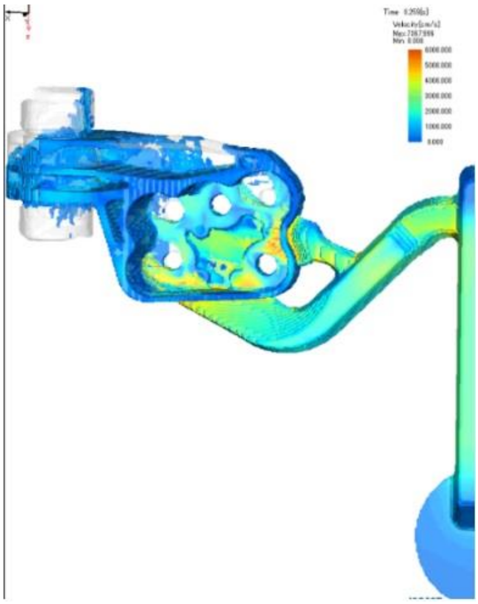
Figure 3. Sticking situation results a) Molten material hitting the pin b) No risk for the pin

2.2.3. Filling of Airflow before the Part

The filling of the molten alloy into the airflow is an important problem that must be examined during the simulation. If the airflow is fulfilled with alloy before the part, there is a high probability that a turbulence will form in the die after injection and this leads to porosity.



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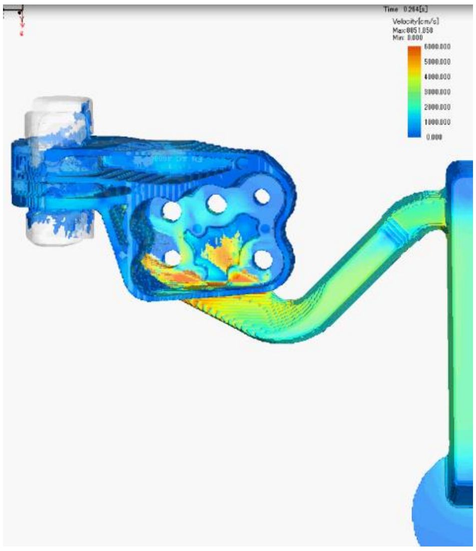

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Figure 4. Filling of airflows a)Turbulence in the die b) Smooth flow in the die

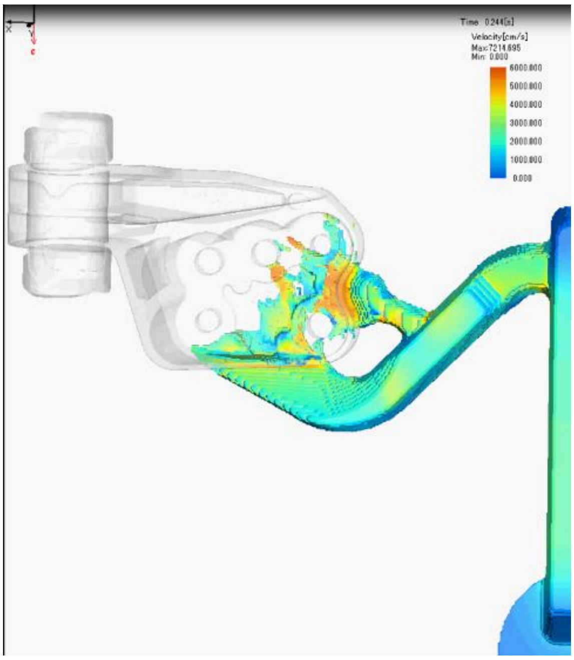
When figure 4.a is examined, because turbulence occurs in the two-runner design, the airflows are filled with metal. Meanwhile, the inside of the die is not completely filled. The material entering the airflow will fulfill the airflow and move towards the inside of the die. This will cause the formation of porosity in the part. The material flow simulation for the single runner design is shown in figure 4.b. As can be seen from the figure, in such this design, the airflow is filled with material after the whole piece is fulfilled.

2.2.4. Metal Flow

As seen in the simulation in figure 5.a, there is a fast and hot flow direction from the large runner to the thick wall of the part for the two-runner design. The metal entering through the smaller runner follows a different flow direction. While the molten aluminum entering from the large runner moves upwards, the molten aluminum entering the die from the small runner on the right flows directly across. Thus, molten metal coming from two different directions collides with each other inside the die. This situation creates turbulence at the entrance of the die and traps the air inside, causing porosity. For the single runner design in 5.b, the metal flow is in one direction, as it can be seen. In this case, there is a laminar flow and the possibility of porosity is reduced.

2.2.5. Inspection of Porosity

The last step before the dies are processed, the possible porosity sizes and ratios are examined by using the simulation program. According to the porosity standards, depending on the wall thickness of the piece being examined, the porosity images are divided into 2 sections and 4 levels depending on the ASTM criteria. The wall thickness of the part to be injection molded is less than 9.5 mm in some places and larger in some places. Accordingly, it is possible to make a comparison by using the tables and images in the "Standard Reference Radiographs for Inspection of Aluminum and Magnesium Die Castings" ASTM E505 (2011). When figure 6.a and figure 6.b are examined together, the porosity number and density are much less for the single runner design. The dots in the image represent the porosity. The change in the color of the dots from blue to orange gives an idea about the size of the porosity that will occur in that region.



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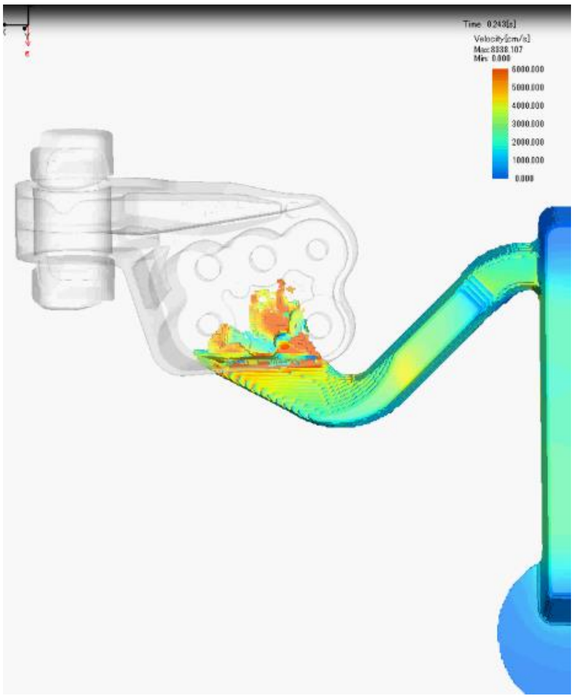

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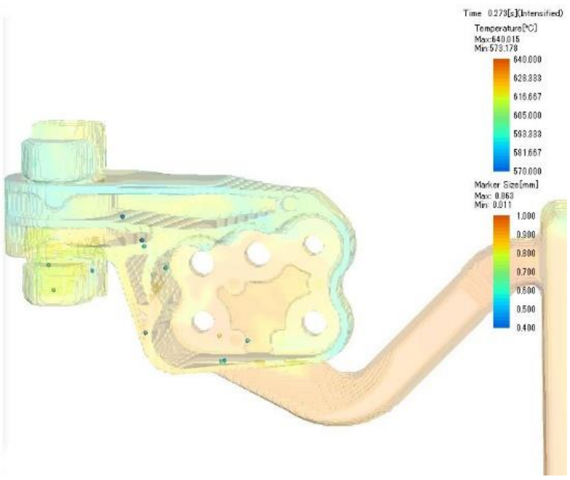
Figure 5. Metal flow simulations a)Turbulence in the die b) Smooth flow in one direction



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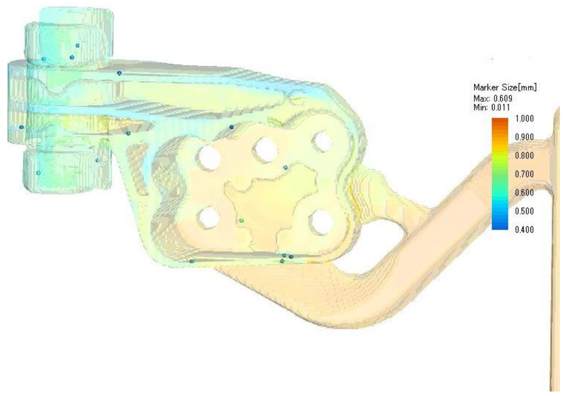


b)

Figure 6. Porosity formation points a) Size and number for single runner design b) Size and number for single runner design

Thus, based on the controls listed in the 5 sub-headings given above, it is clear that it is appropriate to choose the design with single runner and four airflows.

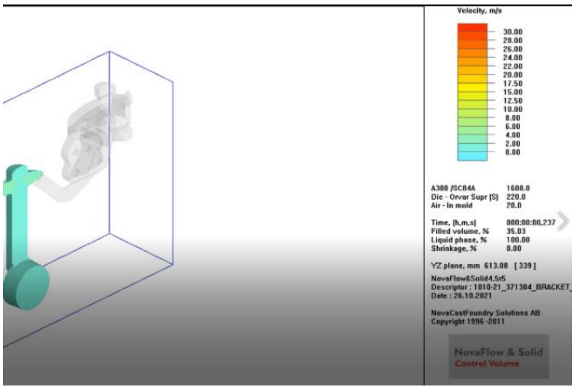
2.3. Detection of the Lenght of the Switch Point

In the HPDC method, the liquid metal fills the die in a total of 3 phases. The 1st phase velocity is the velocity at which the piston first strikes when the automatic ladle transfers the molten alloy to the machine. As the piston transfers the molten alloy into the die, there is a transition from the 1st to the 2nd phase. The place in the transition from the 1st to the 2nd phase is called the switch point and it is the point that needs the most attention in simulation studies. When the injection process passes to the 2nd phase at the switch point, the molten aluminum takes the shape of the die and the injection ends here. After this stage, the third phase begins. While velocity is an important parameter in the first two phases, the parameter to be considered in the third phase is pressure.

After deciding on the one-way (single runner) design, the next step is to determine the switch point and the speed of the 2nd phase, as known plunger speed also. The material is pushed towards the runner at a slow speed of about 0.25 m/s from the biscuit (1st phase speed). After a filling of approximately 40% and without material entering the main part, the 2nd phase speed is started. The second phase plunger speed is the speed of the piston pushing the material into the die. Injection process is performed at high speed in the 2nd phase speed. In the presented study, simulations were made for 2 different switch point distances. Considering the simulation results, the most appropriate point was determined. Then again, the simulation images were examined and the 2nd phase plunger speed selection was made for the switch point position.

2.3.1 Determination of the Switch Point Location

The switch point should be close to where the feeder runner ends and the part entry runner begins. At this point, the injection speed is increased and the second phase is started. The first simulation attempt was made for a 60 mm switch point length and its simulation is shown in figure 7.a. When the switch point is at 60 mm and the system is still at phase 1, the filling volume is approximately 35%. As seen in figure 7.b, when the second phase speed is activated, the first color change occurred for 36% filling volume. At this time, the material has not yet completely filled the runner and the metal has not reached the part inlet. Therefore, 60 mm switch point is not the desired parameter.



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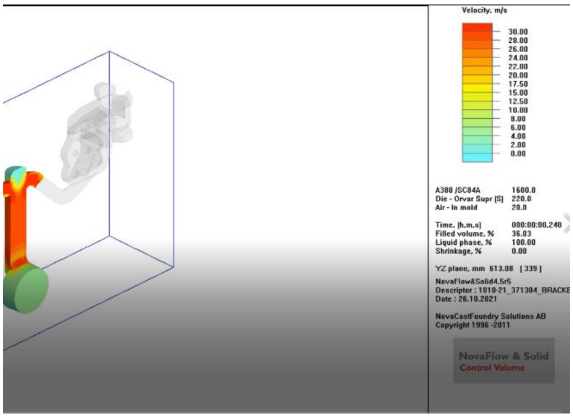

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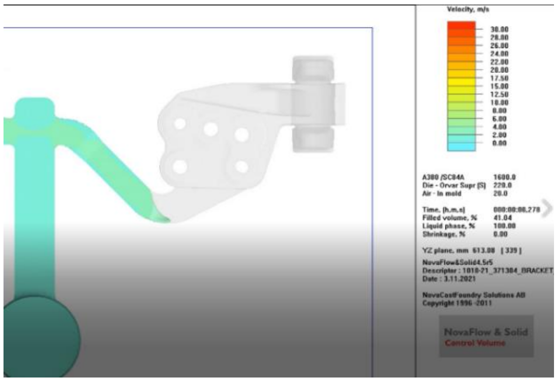
Figure 7. Switch point length simulations a)1st phase for 60 mm b)2nd phase for 60 mm

If the switch point is selected as 70 mm, the filling volume just before switching to the second phase speed is 41%. Moreover, as can be seen in figure 8.a, the runner is almost completely filled with material. At this point, the second phase speed is activated and a color change is observed on the simulation scale. At this point, the filling volume also increased to 42% as shown in figure 8.b. Since the start of the second phase speed should be done when the material is very close to the mold, it is appropriate to choose the switch point as 70 mm.

2.3.2 Determination of 2nd Phase Plunger Speed

The most important parameter in the selection of the second phase speed (plunger speed) is the die filling speed of the metal. While the liquid metal fills the die and takes the shape of the part, there should be no freezing.



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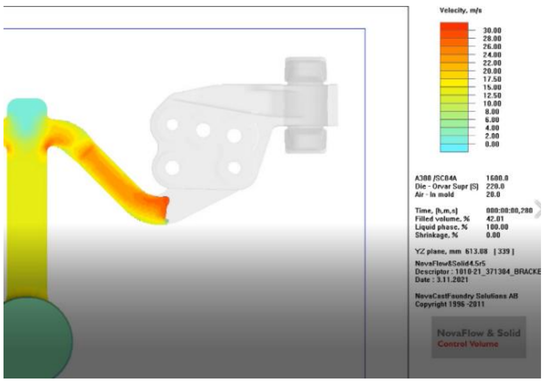

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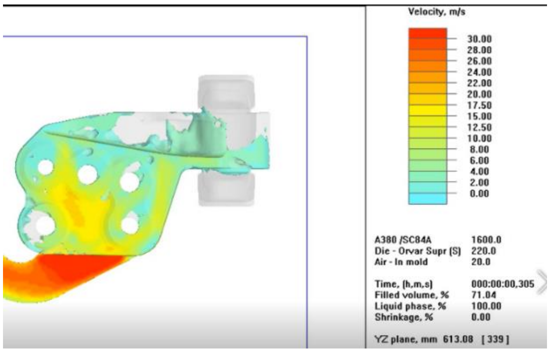
Figure 8. Switch point length simulations a)1st phase for 70 mm b)2nd phase for 70 mm

Unexpected freezing will cause incomplete filling of the part. Moreover, there is a risk of porosity and cold bonding. In the presented study, 2 m/sec, 4 m/sec and 6 m/sec speed values were simulated as the plunger speed for the 70 mm switch point as determined before. The simulations are planned to examine the material filling of the die in equal time intervals. Simulation images for 3 different second phase speeds are presented in Figure 9.

Figure 9.a shows the filling simulation for the 2 m/sec second phase speed. It is impossible to fill the die at this speed. Because there are gaps around the pin holes when the filling ratio is at 71%. There is a filling speed of about 15 m/sec in the middle of the piece. However, since the speed around the pin holes is null according to the color scale, there is no material movement and it is not possible to fill those spaces with material. It is inevitable that the freezing or cold joining problem will occur.



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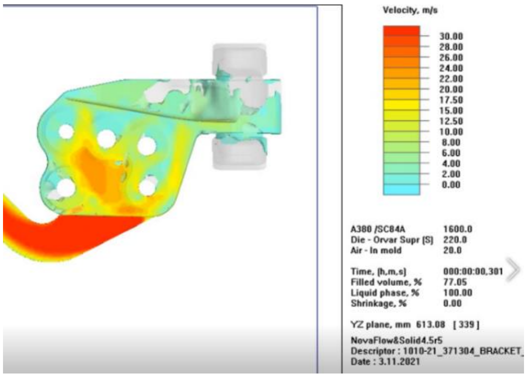

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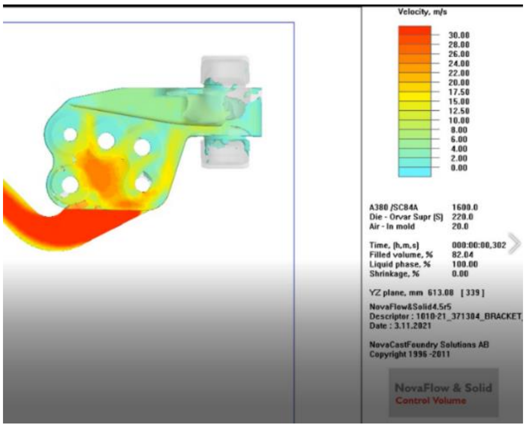


c)

Figure 9. Plunger speed simulations

a) for 2m/sec plunger speed b) for 4m/sec plunger speed c) for 6 m/sec plunger speed

Since the 2 m/sec second phase speed did not perform a successful filling, a new simulation study was carried out by choosing the second phase speed as 4 m/sec. At this speed, the filling ratio has increased to 77% as seen in Figure 9.b, but there are still places where the material is not filled. The velocity in the middle part of the piece is around 18 m/sec.

However, the near region of the pin holes is still not filled. Moreover, the flow rate here is null. At this speed, the probability of formation of porosity in the part is very high.

The last injection speed trial was performed for 6 m/sec in the same time period as the first two injection speeds. At this speed, the part is almost completely filled with the material as seen in Figıre 9.c. The filling ratio is around 82% when evaluated together with the air flows. The material velocity in the middle part of the piece is around 22-24 m/sec, and the near area of the pin holes is mostly filled. There is sufficient material speed in the part for material flow to unfilled areas.

a)

b)

Figure 10. Representation of the die a) fix side of the die b) moving side of the die

3. Manufacturing of the Die and Selection of the Material

In the light of all these data, it was decided that the speed of the second phase, which we can also express as the plunger or injection speed, should be 6 m/s. Based on the simulation results explained above, it was decided that the design would be as single runner. The number of airflows will be four considering the literature information. Two of the air flows are designed to be on the moving side of the die and two on the fixed side of the die. The switch point length was determined as 170 mm in accordance with the simulation images. As a result of the simulation studies, the technical drawing of the die was drawn and manufactured in the appropriate size and geometry, and it is shown in Figure 10.

The experiments were carried out on a 750-ton hot chamber high-pressure injection machine. Al-Si based die casting alloy EN-AC 46000 AlSi9Cu3(Fe) was chosen for the present study. The chemical compositions of the alloy used are presented in Table 1.

Table 1. Chemical composition of grade EN-AC 46000-AlSi9Cu3(Fe) (weight%)

Fe	Si	Mn	Ni	Cr	Ti
max. 1.3	8-11	max. 0.55	max. 0.55	max. 0.15	max. 0.25
Cu	Pb	Mg	Zn	Sn	Al
2-4	max. 0.35	0.05-0.55	max. 1.2	max. 0.15	remainder

4. Results and Discussion

A sample part produced by the HPDC method is shown in Figure 11. As a result of the naked eye examination, it is seen that the part does not have a region remaining in the mold or sticking to the mold. Moreover, no adverse events such as breakage or freezing were encountered. Thus, the simulation studies were confirmed.

Figure 11. Casted Part

4.1. Radioscopic Examination

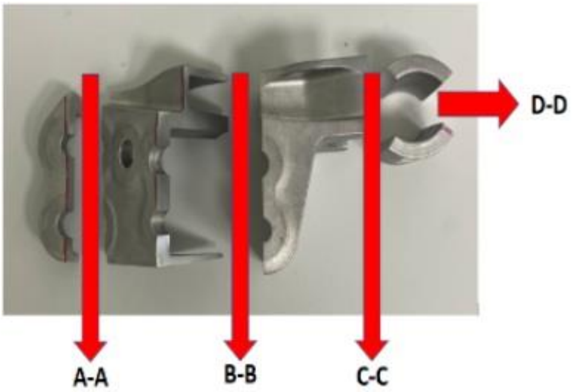
As mentioned before, the simulation studies focused on surface quality and porosity. After it was understood that there was no problem in the visual control, it was time for the porosity control process. Porosity analysis was performed on the Yxlon Computed Tomography X-ray device. The examinations were made for regions with a wall thickness of 9.5 mm and more, in accordance with the relevant standards. The aim is to comply with the ASTM E 505 Level 2 standard. Obtained results are presented in Table 2. A small amount of microporosity was seen on the piece and was below the level 2 standard. In addition, cold flow, shrinkage cavity and foreign material determination were not made.

Table 2. Radioscopic examination results

Porosity	Micro porosity. Acceptable for ASTM E 505 LEVEL 2
Cold Flow	No detected any cold flow limit of ASTM E 505 LEVEL 2
Shrinking Cavity	No detected any shrinking cavity limit of ASTM E 505 LEVEL 2
Foreign Material	No detected any foreign material limit of ASTM E 505 LEVEL 2

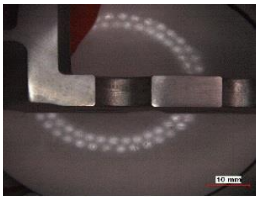
4.2. Porosity Examination with Microscope

As can be seen in Figure 11, the mounting areas of the cast part, whose wall thickness is less than 9.5 mm, but which must provide a certain strength value, were cut and also porosity analysis was carried out. The section planes and the cut of the parts are shown in Figures 12.a and 12.b. After the cutting process, polishing was done and then porosity determination was started. In this test, the expectation is to find out whether the largest porosity diameter is less than 0.5 mm in regions with a thickness less than 9.5 mm according to ASTM E 505 Level 2. The second important parameter is the ratio of the porosity area to the total area. As a result of the examination, the porosity was found only in the A-A section plane. The results are presented in Table 3.

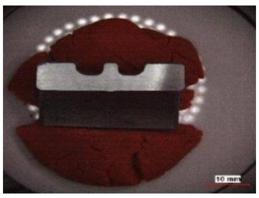


a)

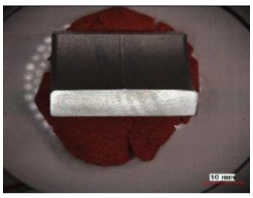
A-A Section



B-B Section



C-C Section



D-D Section

b)

Figure 12. Section planes of the part
a) Cutting directions b) Plane images of all sections

Table 3. Prosity examination results of A-A section

The biggest porosity diameter	0.379 mm
Porosity area	0.1128 mm^2
Total examined area	48.715 mm^2
Ratio	% 0.20

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Conflicts of Interest Statement

The authors declare that there is no conflict of interest.

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