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EFFECTS OF AIR-COOLING-HOLE GEOMETRIES ON A LOW-PRESSURE DIE-CASTING PROCESS

VPLIV GEOMETRIJE KANALOV ZA ZRAČNO HLAJENJE NA PROCES NIZKO TLAČNEGA LITJA

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A significant precondition for the production of high-quality castings is keeping an optimum temperature of the respective parts of the die cavity surface. This temperature depends on the temperature of the material, the quantity of metal, the method of cooling the casting die, the thermal conductivity of the die material, and the time during which the casting remains in the die. In addition, the cooling characteristics of alloy steel dies, used in the production of aluminum-alloy wheels with the low pressure die casting (LPDC) method, have critical effects on the mechanical and metallurgical properties of the product. Ducted air coolers are widely used for the cooling of these alloy steel dies. However, the geometrical designs of the air-cooling holes are limited. In this study, we define the effects of the geometry of the cooling holes on the cooling power of the die, the efficiency of the air consumption with the Full Factorial Experimental Design method and to determine the optimum values for LPDC. Pilot production has been carried out on an industrial scale to verify the data obtained by experimental design. The experimental and real data were compared based on the values of the yield strength and the secondary dendrite arm spacing in the microstructure.

Keywords: low pressure die casting, colling system, die design, aluminum-alloy wheels

Pomemben pogoj za izdelavo visoko kakovostnih ulitkov s postopkom nizko tlačnega litja (LPDC; angl.: Low Pressure Die Casting) je ohranjanje optimalne temperature na površini orodja. Ta temperatura je odvisna od materiala, kvalitete livne kovine, metode hlajenja orodja za litje, toplotne prevodnosti materiala (orodnega jekla) iz katerega je izdelano orodje in od časa, ko se ulitek zadržuje v orodju. Dodatno imajo ohlajevalne karakteristike orodnega jekla, uporabljenega za proizvodnjo litih avto platišč iz aluminija kritičen vpliv na mehanske in metalurške lastnosti ulitka. Zračni hladilni kanali se na splošno uporabljajo za hlajenje teh legiranih orodnih jekel. Vendar ima oblika (geometrijo) kanalov za zračno hlajenje omejitve. V članku avtorji opisujejo študijo vpliva geometrije hladilnih kanalov na učinkovitost hlajenja orodja, učinkovitost porabe zraka s FFED (angl.: Full Factorial Experimental Design) metodo in določitvijo optimalnih vrednosti za izbrani postopek nizko tlačnega litja. Izvedli so pilotno proizvodnjo na industrijskem nivoju za verifikacijo podatkov dobljenih z eksperimentalnim dizajnom. Avtorji so med seboj primerjali realne in eksperimentalne podatke glede na mehansko trdnost ulitkov in razdaljo med sekundarnimi dendritnimi vejami v mikrostrukturi ulitkov zlitine.

Ključne besede: nizko tlačno litje, hladilni sistem, oblikovanje (dizajn) orodja, avtomobilska platišča iz aluminijeve zlitine

1 INTRODUCTION

Low-pressure die casting (LPDC) is widely used for manufacturing aluminum-alloy wheels. In this method, the liquid aluminum metal in an air pressure-controlled furnace fills the die by rising in a vertical way through the low pressure applied to its surface. After that, the air pressure is lowered and the excess liquid metal remaining in the sprue well is returned to the furnace. Following this, solidification is achieved by cooling owing to the heat transfer from the filled cavity to the die. As a result of the process, die parts are separated and the final product is obtained.[1,2] The heat transfer and solidification regime should be kept under control during cooling in order to improve the mechanical and metallurgical properties of the aluminum-alloy casting products. The microstructure and mechanical properties of casting products are strongly related to the cooling rate (CR) during solidification and the CR has a major effect on these properties.[3,4] More small-sized dendrites are formed at higher cooling rates,[5] owing to which the degree of shrinkage decreases, resulting in the casting exhibiting more uniform mechanical properties Hence, the cooling of the die, which has a significant effect on the cooling rate of the cast, is the vital step in this process. On the other hand, other parameters such as the type and thickness of the die coating, the gap formation between the die and the cast, the applied pressure directly affect the cooling rate, hole geometry and the type of cooling in a die.

Generally, the microstructure of the cast part is refined by increasing the heat extraction and corresponding increase in the solidification rate on LPDC. In fundamental and theoretical studies, the casting structure is often represented as unidirectional and columnar, with grains or branches represented by cylinders with rounded tips. In fact, the microstructure of a commercial alloy casting consists of dendrite equi-axed grains.[6] The

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microstructure is therefore considered on two levels: the grain size and the dendrite arm spacing. The grain size is a function of several parameters, the most important of which are the nucleation rate and the growth rate. The nucleation rate depends on the amount of energy required for the creation of a new phase structure and new surface area. Therefore the nucleation rate can be affected by the melt under cooling below the liquidus (which gives a direct thermodynamic stimulus for nucleation, decreasing the critical size of the solidification nucleus) established a power relationship between the thermal parameters and secondary dendrite arm spacing.[6,7] His hypothesis suggested that a longer solidification time results in a slow CR, hence allowing enough time for a remelt for the dendrite arm spacing. This results in large sized dendrite arms with a large dendrite arm spacing.

The condition of the contact interface between a casting part and the die has a significant effect on the heat transfer and hence the solidification time. The heat transfer between a casting and the die is significantly related to the die coat[8] until an air gap[9,10] forms between the contact interface. This air gap, which acts as an insulating layer, also has a significant effect on the heat-transfer process.[11] Ilkhchy et al.[12] investigated the effect of the applied air pressure on the cooling rate of the cast. Their results suggest that the pressure has a strong, positive effect on the cooling rate. In another study, Pietrowski and Wladysiak[13] used an air and water mixture instead of air for cooling a die used for aluminum-alloy wheels. They could reduce the time of casting by 28 % and obtain better mechanical properties compared to the case where the die was cooled with air. Based on these results, it can be said that adding some water to the air increases the cooling rate of the die. Due to the determination of air cooling design parameter's effects such as hole diameter D (mm), the inner diameter of the nozzle d (mm), distance between the tip of nozzle and bottom of hole x (mm) on solidification, microstructure, grain size distribution and mechanical properties of cast part, synthesis, structure, properties and performances relationship could be obtained in the area of material science.

Design of experiments (DOE) is a reliable and robust statistical method for identifying the relationship between a set of input variables and an output(s). It is used to determine the best combinations of the input variables or design parameters to ensure the desired outputs.[14,15] According to this, DOE is applied to determine the geometry effect of cooling holes in dies. LPDC dies for aluminum-alloy wheels have many specially located blind holes that are used for air cooling. A cooling circuit is a network of pipelines that supplies air at 8 bars into a group of holes. The number of holes in a group is usually 4–10. Furthermore, one die can have more than 10 cooling circuits. Using a thinner pipe connected to the circuit, called the air nozzle, compressed air is blown into the holes. While the temperature of the air is approximately 25 °C, the temperature of the blind hole surfaces can be as high as 500 °C during the filling of the casting. The injected air strikes the bottom of the blind hole first and then the side walls and escapes through the open side of the hole into the atmosphere, thus cooling the die.

As explained above, although there are many studies in the literature regarding the process parameters, there are few studies on the geometrical parameters of cooling holes in dies used for aluminum-alloy wheels. The main aim of this study was to elucidate the effects of the cooling-hole geometry of LPDC dies for aluminum-alloy wheels on the cooling power and effectiveness of air consumption in order to determine the mechanical property variations of the wheels and the design criteria for the cooling holes of these dies.

2 EXPERIMENTAL PART

2.1 Analysis of Experimental Method

One of the experimental findings obtained using the test stand was that the same or a slightly greater level of cooling power can be achieved than that possible currently, while consuming 29 % less air merely by changing the value of d from 4 mm to 2 mm. This was confirmed using the production line. For this purpose, two different dies for AlSi7 and AlSi11 alloy wheels were modified (redesigned) as per this finding and used to cast more than 400 wheels. The yield strength and secondary dendrite arm spacing (SDAS) values of the wheels were considered as indicators of the cooling power. A comparison of the yield strength and SDAS values of the cast wheel samples, measured before and after the modification suggested that the experimental results obtained from the test stand and the production line were consistent.

Determining which parameters affect the heat transfer in the case of cooling holes based on heat-transfer equations is not possible, given the dynamic thermal characteristics of the problem. Therefore, a three-factors-at-two-levels full-factorial method that included three replicates and two center points was used to define the experiments and elucidate the relationships between the cooling power of the holes (P_c), the effectiveness of the air consumption (E_{air}), and the following parameters: hole diameter (D), nozzle inner diameter (d), and distance between the hole bottom and the nozzle tip (x). These parameters were defined as the crucial input factors. To reduce the effect of noise factors as well as limit the resources required, instead of a production line, a test stand equipped with a prototype die and measuring and controlling devices was used to perform the 26 defined experiments. The experimental results are presented using box plots to show the distributions of P_c and E_{air}. The effects of each input factor on P_c and E_{air} as well as their interactions were determined using the statistical method called analysis of variance. The factors resulting in the maximum cooling power and most effective air con-

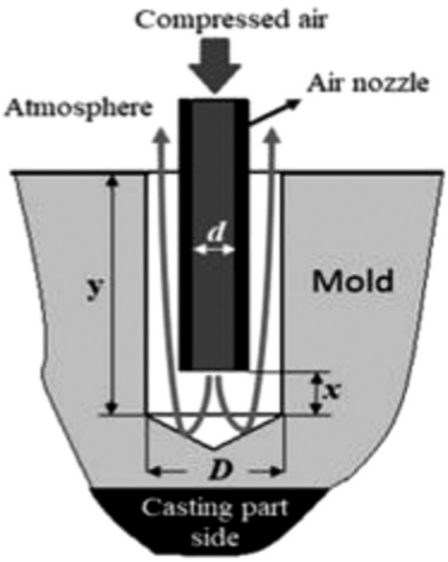

Figure 1: Illustration of air cooling of die for casting

sumption for the air cooling of the dies were identified. Further, there is a close link between the cycling time of the casting part and the cooling of the die. Therefore, the air used as a cooling fluent should be used as efficiently as possible to reduce the production costs while ensuring that the cast parts meet the quality requirements. Full factorial experiment (FFE) design is suitable for studying all possible combinations of the different levels of the various factors involved in an experiment. FFE design is also suitable for studying the effects of the interactions between the factors on the response. Two center points were added to test the existence of a nonlinear relationship between the factors and outputs.

The parameters *D*, *d*, and *x* (as seen in **Figure 1**) were chosen as the critical controllable geometric design parameters for the holes. The values of *D*, *d*, and *x* used currently are 12 mm, 4 mm, and 5 mm, respectively. Since the thickness of the cross-section of the die defines the hole depth, denoted by y in **Figure 1**, it was considered an uncontrollable factor for the cooling design and was not considered in this study. When the factors have two levels, the low and high levels can be represented as –1 and +1, respectively.[16] The levels of the selected parameters used are listed in **Table 1**. The design limitations and current engineering knowledge determined the high and low values of these factors. The configurations of the required experiments as per the defined DOE method are given in **Table 2**.

Table 1: Levels of design and process parameters

Parameters (Factors)	Levels	
	–1	+1
Hole diameter, *D* (mm)	12	16
Inner diameter of nozzle, *d* (mm)	2	4
Distance between tip of nozzle and bottom of hole, *x* (mm)	5	15

Table 2: Configuration and number of repetitions of experiments

Configuration number	*D*/mm	*d*/mm	*x*/mm	Repetition
1	12	4	5	3
2	12	4	15	3
3	12	2	15	3
4	12	2	5	3
5*	14	3	10	2
6	16	4	5	3
7	16	4	15	3
8	16	2	15	3
9	16	2	5	3

*Denotes center points

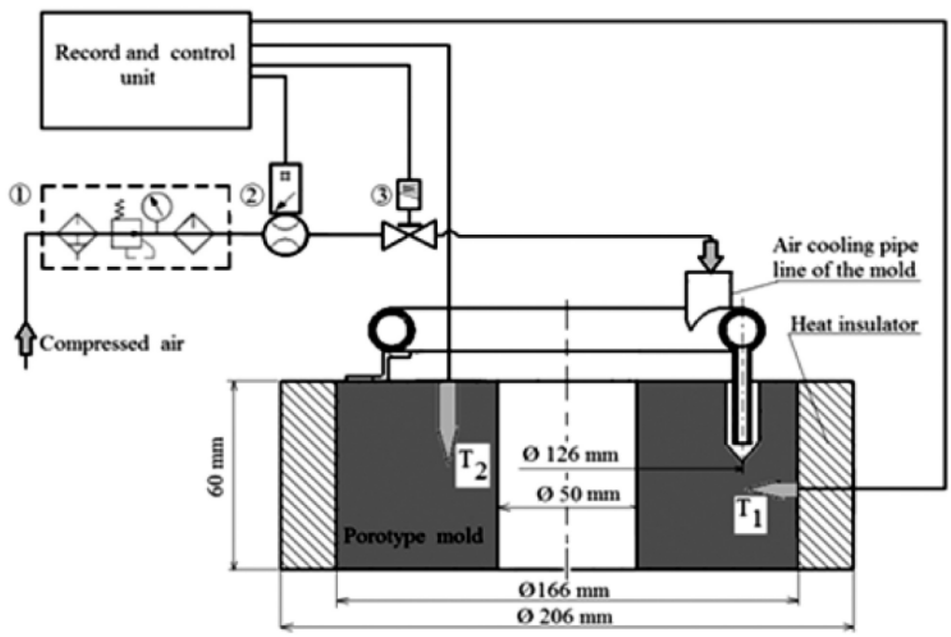

Figure 2: Schematic of the test stand

2.2 Experimental set up

To reduce the effects of noise factors as well as the resources needed, instead of a production line, a test stand, shown in **Figure 2**, was set up to perform the experiments. The material used for the prototype die was a standard H13 hot-work steel, which is a common die material for LPDC dies. The dimensions of the die are given in **Figure 2**.

The die was insulated to minimize the heat transfer to the environment. Five cooling holes were present on the die and there was an angular space of 72° between them. The depth of the holes and the outside diameter of the nozzles were 30 mm and 6 mm, respectively. Note that the placement of the cooling holes was typical for the dies used for aluminum-alloy wheels. Two thermocouples, T1 and T2, were placed in the die. While T2 was used to measure the average temperature of the die, T1 was used to measure the temperature at a location 10 mm below the cooling hole. The pressure, temperature, and relative humidity of the air were kept at 8 bar, 35 °C, and 17 %, respectively. As shown in **Figure 2**, a standard air-preparation unit (1), flow sensor (2), and solenoid valve (3) were installed on the air pipeline, whose inner diameter was 14 mm. The air flow sensor used was a SFAM-90-1500L-TG112-25 sensor from FESTO.

The record and control (RC) unit had a paperless recorder with a touchscreen (E-PR-100, Elimko) with configurable six-channel universal inputs and six relay outputs. The unit could read and record the signals coming from the flow sensor and the thermocouples. It was also programmed to control the solenoid valve to initiate the air flow when the representative die specimen's temperature reached 490 °C and to stop it when it fell below 320 °C. Note that these temperatures constitute the typical working range for the dies used to cast aluminum-alloy wheels.

The following procedure was performed for each experiment: (i) the die was heated to 520 °C from its bottom surface. Then, the heating of the die was stopped, and the die was permitted to cool to 490 °C to ensure that it had a uniform temperature distribution. (ii) When the temperature dropped to 490 °C, the RC unit was used to start the air flow to the air holes of the die. (iii) The unit was used to stop the air flow when the temperature dropped to 320 °C. During this cycle, the temperatures measured by thermocouples T1 and T2 as well as the air flow rate, air consumption, and time were recorded by the RC unit.

2.3 Verification tests

The experimental results obtained using the test stand should have been verified using a production line. However, verifying every result, which would have required a lot of effort and resources, was not feasible. Instead, we verified only one of the results. This result indicated that the same cooling power can be achieved while consuming 29 % less air simply by changing the value of *d* from 4 mm to 2 mm. For this purpose, two LPDC dies for aluminum-alloy wheels employed in serial production were used. Alloy types of first and second wheel, named Model 1 and Model 2, are AlSi11Mg and AlSi7Mg, respectively.

The cooling holes of the circuits had different depths (10–50 mm), and the cooling time of the holes was 30–80 s. The inner diameter of the nozzles in the cooling holes was changed from 4 mm to 2 mm, with the exception of the nozzles in cooling circuit 6, which had a completely different cooling design. More than 400 pieces were cast using each die in this manner without changing any process and quality parameters.

Table 3: Cooling details for Model 1 and 2

Cooling circuit	Number of cooling holes (Model 1)	Number of cooling holes (Model 2)
1	10	10
2	5	5
3	10	15
4	10	5
5	10	10
6*	1	1
7	5	7
8	10	8
9	10	-
10	10	-

*This cooling circuit had an entirely different design and was not modified.

The air consumptions of the cooling circuits per casting cycle were measured both before and after the modification process by using the flow sensors present on the LPDC machine. The air-consumption measurements were repeated three times, and the average values were considered and compared.

Round tensile-test specimens were prepared from the spokes and inner and outer rims of the wheels according to the DIN 50125 standard. The tensile tests were performed three times for each region using a Roell Z100 (Zwick) test machine. The average values of the yield strengths of the test specimens were determined and compared with those measured before modification. Also, the scrap rates of the fully processed wheels determined before and after modification were compared. The SDAS is an important microstructural property for aluminum alloys. The cooling rate or solidification time has a significant effect on the SDAS values. As the cooling rate, which is related to the efficacy of the cooling holes of the die used, is increased, the SDAS value decreases, while the mechanical properties of the cast specimen improve. Therefore, the SDAS values were measured at 7 different regions from the inner flange to the spoke of a wheel. These values were also compared with those obtained before modification.

3 RESULTS AND DISCUSSION

3.1 Experimental results

The results of the experiments are listed in **Table 4**, while box plots of P_c and E_{air} are shown in **Figure 3**. The box plot displays the full range of the variations and mean values of P_c and E_{air} for each configuration of the experiments listed in **Table 2**. The following conclusions can be drawn from **Figure 3**. Firstly, the horizontal axis in **Figure 3** presents the configuration number of the experiments. The mean values of P_c and E_{air} are written near the related box. Number 1 on the horizontal axis represents the existing values of the factors, with the values of *D*, *d*, and *x* being 12 mm, 4 mm, and 5 mm, respectively. $E_{air}(1)$ is 0.348 kW/m^3, which is the second-worst value among the nine values. Note that while $P_c(4)/P_c(1)$ is almost equal to 1, $E_{air}(4)/E_{air}(1)$ equals 1.408. Assume that we need 1 kW of cooling power. In that case, the air consumption levels for configurations 1 and 4 would be 2.874 m^3 and 2.040 m^3, respectively. This means that 29 % less air is consumed for the same cooling power (100 × (2.874 – 2.040) / 2.874 = 29 %).

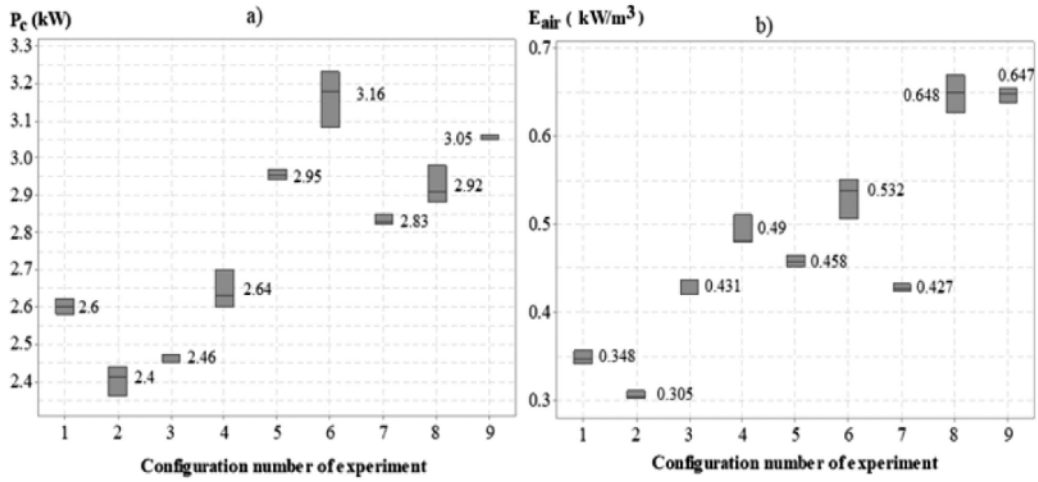

Figure 3: Box plots of the experimental results

Table 4: The results of experiments

Standard Order	Run Order	Center Points	Block	*D*/mm	*d*/mm	*x*/mm	P_c/kW	E_{air}/kW·m^{-3}
3	1	1	1	12	4	5	2.58	0.341
11	2	1	1	12	4	5	2.6	0.346
19	3	1	1	12	4	5	2.62	0.357
7	4	1	1	12	4	15	2.44	0.311
15	5	1	1	12	4	15	2.41	0.303
23	6	1	1	12	4	15	2.36	0.302
5	7	1	1	12	2	15	2.47	0.437
13	8	1	1	12	2	15	2.45	0.420
21	9	1	1	12	2	15	2.47	0.437
1	10	1	1	12	2	5	2.6	0.481
9	11	1	1	12	2	5	2.7	0.510
17	12	1	1	12	2	5	2.63	0.480
25	13	0	1	14	3	10	2.97	0.464
26	14	0	1	14	3	10	2.94	0.452
4	15	1	1	16	4	5	3.23	0.551
12	16	1	1	16	4	5	3.18	0.538
20	17	1	1	16	4	5	3.08	0.506
8	18	1	1	16	4	15	2.83	0.423
16	19	1	1	16	4	15	2.82	0.426
24	20	1	1	16	4	15	2.85	0.432
6	21	1	1	16	2	15	2.91	0.650
14	22	1	1	16	2	15	2.98	0.669
22	23	1	1	16	2	15	2.88	0.626
2	24	1	1	16	2	5	3.05	0.649
10	25	1	1	16	2	5	3.05	0.638
18	26	1	1	16	2	5	3.06	0.655

Secondly, the maximum cooling power, $P_c(6) = 3.16$ kW, is obtained when the values of *D*, *d*, and *x* are 16 mm, 4 mm, and 5 mm, respectively. Although these values result in the maximum cooling power, $E_{air}(6)$ is 0.53 kW/m^3, which is close to the average value of E_{air} for the experiments. Thirdly, the most effective air consumption, E_{air} (8,9) $\approx$ 0.648 kW/m^3, is obtained when the values of *D* and *d* are 16 mm and 2 mm, respectively.

3.2 Analysis of results

ANOVA was used to test the significance of the factor effects. The results of ANOVA for P_c and E_{air} are listed in **Tables 5a** and **5b**, respectively. Minitab® was used for ANOVA as well as for all the plots presented in this section. The alpha level, denoted as α, is the probability of rejecting the null hypothesis when it is true. Usually, an alpha level of 0.05 is assumed and indicates that the margin of error is 5 %. Thus, α was taken as 0.05 for ANOVA. The *P* value is the probability that measures the evidence against the null hypothesis. If the *P* value of a source in the table is less than α, it has a significant effect on P_c or E_{air}. On the other hand, if the *P* value is equal to or greater than α, the source has no significant effect. In **Tables 5a** and **5b**, DF, Seq SS, Adj SS, and Adj MS are the total degrees of freedom, sequential sums of squares, adjusted sums of squares, and adjusted mean squares, respectively. The parameter "contribution" shows the proportion (in percentage) that each source in the ANOVA table contributes to the total Seq SS. If the source has a higher percentage, it has a greater effect on the variation in the response.[17]

Table 5a shows that all the factors (except for *d*, two-way interaction between *d* and *x*, and three-way interaction between *D*, *d*, and *x*) have an effect on P_c. As the *P* value of the curvature is less than 0.05, at least one of the factors *D*, *d*, and *x* exhibits a nonlinear relationship with P_c. Furthermore, even though the relationship is nonlinear, the contribution of the curvature is 4.10 %. **Table 5b** shows that all the factors, including the two-way interaction between *d* and *x* and that between *D* and *d* as well as the three-way interaction between *D*, *d*, and *x* has an effect on E_{air}. As the *P* value in the case of the curvature is greater than 0.05, there is no evidence that at least one of *D*, *d* or *x* exhibits a nonlinear relationship with E_{air}.

The main effects plots in **Figure 4** display the means for each group for a categorical variable. If the output in-

Table 5: ANOVA for P_c and E_{air}

a) ANOVA for P_c $\alpha = 0.05$							
Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Model	8	1.67553	98.38 %	1.67553	0.20944	129.39	0.000
Linear	3	1.56711	92.02 %	1.56711	0.52237	322.72	0.000
D	1	1.30200	76.45 %	1.30200	1.30200	804.39	0.000
d	1	0.00260	0.15 %	0.00260	0.00260	1.61	0.222
x	1	0.26250	15.41 %	0.26250	0.26250	162.18	0.000
Two-way interactions	3	0.02591	1.52 %	0.02591	0.00864	5.34	0.009
$D \times d$	1	0.00570	0.33 %	0.00570	0.00570	3.52	0.078
$D \times x$	1	0.00260	0.15 %	0.00260	0.00260	1.61	0.222
$d \times x$	1	0.01760	1.03 %	0.01760	0.01760	10.88	0.004
Three-way interactions	1	0.01260	0.74 %	0.01260	0.01260	7.79	0.013
$D \times d \times x$	1	0.01260	0.74 %	0.01260	0.01260	7.79	0.013
Curvature	1	0.06990	4.10 %	0.06990	0.06990	43.18	0.000
Error	17	0.02752	1.62 %	0.02752	0.00162		
Total	25	1.70305	100.00%				
b) ANOVA for E_{air} $\alpha = 0.05$							
Source	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Model	8	0.33741	99.05 %	0.33741	0.04218	222.67	0.000
Linear	3	0.32628	95.79 %	0.32628	0.10876	574.20	0.000
D	1	0.17306	50.81 %	0.17306	0.17306	913.67	0.000
d	1	0.13741	40.34 %	0.13741	0.13741	725.46	0.000
x	1	0.01581	4.64 %	0.01581	0.01581	83.47	0.000
Two-way interactions	3	0.00476	1.40 %	0.00476	0.00158	8.38	0.001
$D \times d$	1	0.00176	0.52 %	0.00177	0.00177	9.34	0.007
$D \times x$	1	0.00000	0.00 %	0.00000	0.00000	0.01	0.930
$d \times x$	1	0.00299	0.88 %	0.00299	0.00299	15.80	0.001
Three-way interactions	1	0.005582	1.64 %	0.00558	0.00558	29.47	0.000
$D \times d \times x$	1	0.00558	1.64 %	0.00558	0.00558	29.47	0.000
Curvature	1	0.000789	0.23 %	0.00078	0.00078	4.16	0.057
Error	17	0.00322	0.95 %	0.00322	0.00019		
Total	25	0.34063	100.00 %				

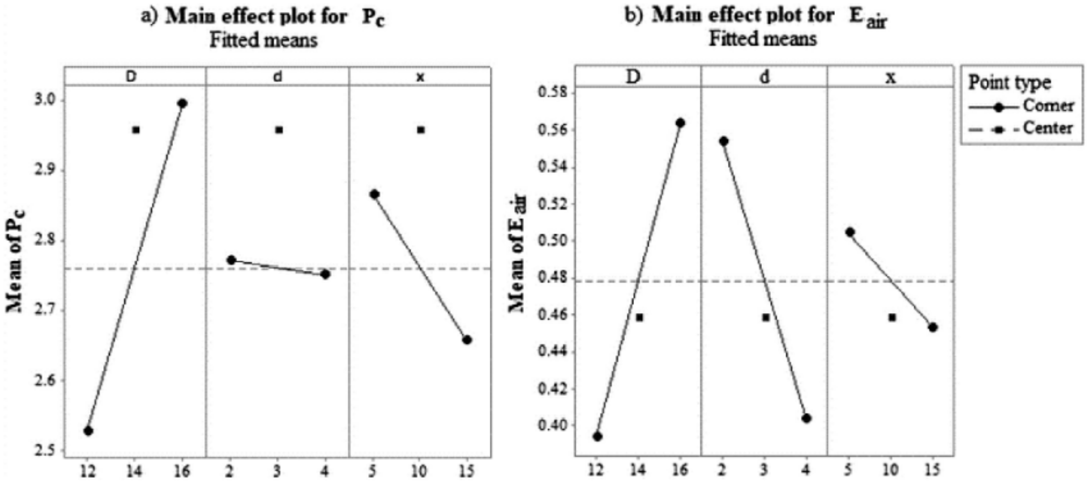

Figure 4: Main effects and interaction plots for P_c and E_{air}

creases when the value of the factor increases, which means that the factor has a positive effect on the outcome. In the opposite case, there is a negative effect. The plots show that while *D* has a positive effect on both P_c and E_{air}, *x* has a negative effect. Furthermore, although d has a negative effect on E_{air}, it has a negligible effect on P_c. Since *d* and *x* have a nonlinear relationship with P_c, the center point does not fit well with the lines in **Figure 6a**.

The ANOVA results and plots presented in this section show that D has the strongest positive effect on P_c and E_{air}. This is reasonable because the area of heat transfer is related to the diameter of the holes. A larger heat-transfer area between the die and the cooling holes raises the temperature of the cooling air to a greater degree, causing an increase in E_{air}. However, owing to design limitations, *D* is usually 12–16 mm. While the effect of *d* on P_c is negligible, it has a major negative effect on E_{air}. Factor *x* has a significant negative effect on both E_{air} and P_c. It can be said that the position of the nozzle in the holes affects the convective heat-transfer coefficient, *h*. The values of *d* and *x* can be set or changed without

Table 6: Comparison of air-consumption values of Model 1-2 per casting cycle

Model Number	Cooling channel number	Modification	Air consumption (liters/casting cycle)							
			Before modification				After modification			
			Order of measurement			Avarage value	Order of measurement			Avarage value
			1	2	3		1	2	3	
1	1	Yes	3178	3205	3189	3191	3039	2994	3094	3042
	2	Yes	3055	3064	3051	3058	2022	2002	2045	2023
	3	Yes	2967	2975	2951	2964	2314	2292	2339	2315
	4	Yes	2148	2150	2133	2144	2011	2003	2043	2019
	5	Yes	2148	2150	2133	2144	2011	2003	2043	2019
	6	No	3471	3479	3453	3468	2974	3442	3520	3312
	7	Yes	3252	3257	3232	3247	2214	2194	2243	2217
	8	Yes	3228	3230	3204	3221	2716	2689	2746	2717
	9	Yes	3303	3300	3279	3294	2721	2695	2758	2725
	10	Yes	3927	3927	3915	3923	3405	3362	3427	3398
	11	Yes	3927	3927	3915	3923	3405	3362	3427	3398
			Total			34575	Total			29185
2	1	Yes	2303	2215	2206	2241	1612	1660	1528	1600
	2	Yes	1858	1774	1763	1798	1364	1412	1274	1350
	3	Yes	667	629	627	641	633	692	629	651
	4	Yes	2123	2030	2019	2057	2012	2082	1881	1992
	5	Yes	1959	1872	1862	1898	1473	1519	1367	1453
	6	No	1948	1858	1846	1884	1681	1744	1573	1666
	7	Yes	727	690	690	702	487	536	481	501
	8	Yes	701	664	662	676	546	600	543	563
			Total			11898	Total			9776
Difference % for Model 1 = 100 × (34575 – 29185) / 34575 = 16 %							Average value = 17 %			
Difference % for Model 2 = 100 × (11898 – 9776) / 11898 = 18 %										

difficulty. However, decreasing the value of *D* would require a new die. Two-level factorial design analysis assumes that the observations are independently and normally distributed.[19] The NPP of the residuals is the best way of checking whether this assumption is true.[20,21] For this purpose, the NPP of the residuals for the responses P_c and E_{air} were obtained and as NPP of the residuals nearly follows a straight line, it was concluded that the residuals are normally distributed.

3.2 Yield strength and SDAS measurements

The air consumption per casting cycle of the models before and after modification are listed in **Table 6**. After modification, the air-consumption values of the models were determined to be 16 % and 18 % lower, respectively. These results are in keeping with the experimental findings obtained using the test stand described above. However, these values are lower than the expected value of approximately 29 %. The reason for this is probably the differences between the parameters of the complete and prototype dies, such as the depth and number of holes in the cooling circuit as well as noise factors.

The comparisons of the average yield strengths of the spoke and inner and outer rims of the models before and after modification are shown in **Figure 5**.

Comparisons of the SDAS values of the models before and after modification is shown in **Figure 6**. It was noted that the scrap rates of the models did not change before and after modification.

From **Figure 5** and **Figure 6** we can conclude that the differences between the two cases are negligible when one considers that the results are based on the casting process. As noted before, there is a close relationship between the CR, microstructural and mechanical properties of the cast products. In this study, the SDAS and yield-strength values, which are important indicator of casting quality, were selected to represent the microstructure and mechanical properties of the cast products, respectively. Consequently, it was clearly seen that the results of the verification tests are matched with the experiment alresults with high precision.

There are various studies in the academic literature investigating the effects of cooling-system designs in low-pressure die casting on process performance and product properties in order to support the motivation of this study. Yavuz and Ertuğrul[22] determined the parameters affecting the performance of the ring-type air-cooling channels used in the production of aluminum wheels using the low-pressure die-casting method by using the computational fluid dynamics software and the working principles of the system were revealed in their study. The flow rate was measured with the change of parameters, such as the number of cooling inlets, the number of cooling outlets, and the pressure, and the results were statistically analyzed. As a result of the study, it was revealed that the cooling system should operate with 6 bar air pressure, have a maximum number of 12 outlets and 2 inlets for optimum cooling performance. In another study, Sui et al.[23] examined the cooling process of an aluminum-alloy wheel during low-pressure die casting, both with simulation and experimental analysis, and investigated the optimization of the solidification time by changing the section thickness in the product. As a result of the study, experimentally measured and virtually calculated temperatures showed that the initial/boundary conditions values were basically in good agreement. In another aspect, it has been revealed that it is possible to design and improve the cooling and insulation processes with simulation studies in reducing porosity in the product and improving the mechanical properties. Ou et al.[24] have developed a new generation simulation-assisted modeling methodology to accurately analyze the temperature change in the die and wheel in industrial low-pressure die casting used in the manufacture of A356 automotive wheels. In the model, there are definitions of resistance to heat transfer especially between mold/casting and mold/water cooling channel interfaces. In order

Figure 5: Comparison of the average yield strength values

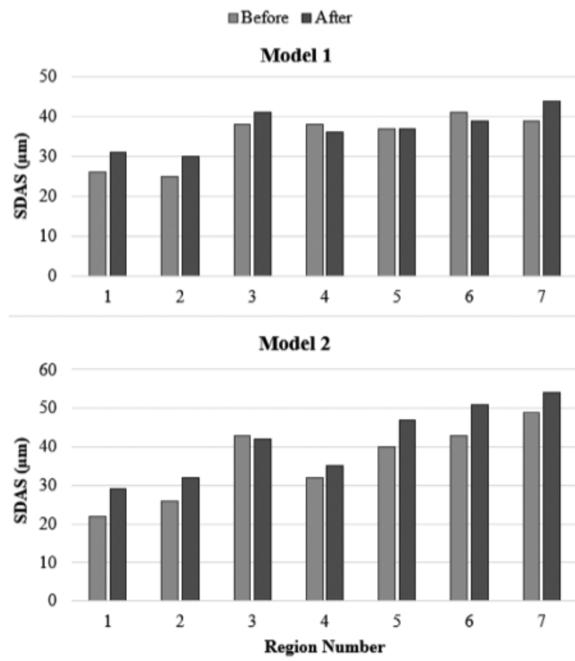

Figure 6: Comparison of the SDAS values

to examine the reliability of the developed methodology, two different dies for water and air cooling combination (Die-A) and only water cooling (Die-B) were analyzed in detail. In both cooling processes, it was observed that industrially measured temperature data and virtual data are compatible. Researches clearly show that the use of experimental design and simulation-supported analysis in the design and development of cooling systems in low-pressure die casting is suitable and effective in terms of the efficiency of the process.

4 CONCLUSIONS

In contrast to the conventional one-variable-at-a-time approaches, the DOE is an effective and scientific way of investigating which geometric design parameters and their interactions affect the cooling power as well as the air-consumption level. The DOE is especially useful if the problem is too complex to apply analytical solutions. Based on the obtained results, the following conclusions can be drawn:

The geometric factors D, d, and x have marked effects on P_c and E_{air}. While D has a significant positive effect on both P_c and E_{air}, factor x has a significant negative effect. Although d has a negative effect on E_{air}, it has a negligible effect on P_c. The relationship between P_c and E_{air} as well as the optimal values of these factors are identified in order to maximize P_c and E_{air}. It is verified that the same or a slightly higher level of cooling power can be achieved while consuming 17 % less air, merely by changing the value of d from 4 mm to 2 mm. The results of this study can be used as design criteria for the cooling holes of dies for the cost-effective production of aluminum-alloy wheels.

Factors d and x have a nonlinear relationship with P_c. Further, the findings indicate that the number of cooling holes is another important factor that affects both P_c and E_{air}. Therefore, methods that account for nonlinearity, such as the response surface or box Behnken method, can be used when considering additional factors such as the depth and number of cooling holes in order to further improve the design criteria for the air-cooling holes in dies.

Yield strength and SDAS values were very close for applied experiments for AlSi7 and AlSi11 alloy wheel rim and spoke.

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