metals

MDPI

Article

Development and Process Integration of an Alternative Demoulding System for High-Pressure Die Casting Using a Contoured Vacuum Mask

Alexander Haban *, **Andreas Schilling**, **Martin Fehlbier, Toni Karalus and Stefanie Felicia Kracun**

Department of Foundry Technology, University of Kassel, Kurt-Wolters-Str. 3, 34125 Kassel, Germany
* Correspondence: alex.haban@uni-kassel.de; Tel.: +49-561-804-7086

Abstract: This study presents the development and process integration of an alternative demoulding system for high-pressure die casting. The system is aimed at the removal of large structural castings, which are becoming increasingly popular in the industry under the terms mega- and gigacasting. The development differs from conventional systems in the fact that it completely avoids ejectors and realises the demoulding via the principle of vacuum suction cups. Preliminary tests were carried out in which various established materials for vacuum cups were initially identified and the suitability of the selected cup concept was investigated by varying influencing variables from the high-pressure die casting. These tests showed that a suction pad material combination of an elastomer with a thermal barrier and an aramid felt on the surface provides the best results under the given process boundary conditions. Based on this, a multi-segmented vacuum mask with contour adaptation to the casting to be removed was developed. This vacuum mask is used to build up the holding force between the casting and the removal device. The necessary removal force is applied via pneumatic cylinders. The functional capability of the concept and the system integration was verified by experiments on a real die-casting mould for test specimens. The shrinkage and demoulding process can be successfully modelled in the simulation and the real measured demoulding force is only approx. 15% higher than in the simulation. During demoulding in the high-pressure die-casting process, vacuums of up to 88.7% were achieved at temperatures up to 395 °C.

Keywords: demoulding system; ejector; high-pressure die casting; contoured vacuum mask; processing innovation

Citation: Haban, A.; Schilling, A.; Fehlbier, M.; Karalus, T.; Kracun, S.F. Development and Process Integration of an Alternative Demoulding System for High-Pressure Die Casting Using a Contoured Vacuum Mask. *Metals* **2024**, *14*, 691. https://doi.org/10.3390/met14060691

Academic Editor: Wenchao Yang

Received: 22 May 2024
Revised: 4 June 2024
Accepted: 7 June 2024
Published: 11 June 2024

1. Introduction

High-pressure die casting is an economical production process for manufacturing automotive components efficiently in terms of quantity, costs, and the weight of the parts. Aluminium and magnesium alloys are primarily used, which have a high potential for lightweight constructions due to their low specific density. The potential of lightweight constructions is decisively influenced by their wall thickness. The thinner the casting, the greater the potential for weight savings. The current trends of light metal castings in the automotive sector show a reduction in the number of parts in the drivetrain due to the transformation of the type of propulsion. The compensation is driven by the search for alternative products in order to continue to utilise production capacities in the future. This has led to increased interest in structural car parts [1].

In particular, Tesla's advance in the area of gigacastings, in which entire front and rear bodies are produced as single castings, is leading to a strong trend in the foundry industry that other manufacturers like Volkswagen, Volvo, Nio, and Xpeng are following [2–4].

The structural parts and mega- or gigacastings all have something in common. These parts are characterised by the substitution of several small parts, functional integration, large surfaces, and long flow paths in combination with thin wall thicknesses. After being poured into a mould, the casting solidifies and undergoes volume contraction as cooling progresses, which leads to shrinkage onto the mould. The castings and their moulded parts are designed in high-pressure die casting in such a way that the casting shrinks onto the moving half of the mould in which the ejector system is located. This leads to surface pressure and then contact pressure between the casting and the mould. Furthermore, the aluminium adheres to the steel, which leads to an additional adhesive force [5].

However, distortion and damage can occur during the demoulding of thin-walled castings. One reason for this is the punctual demoulding force of the ejector pins on the component used in a conventional die-casting mould [6]. Several ejector pins that are centrally driven via the ejector plate are used in these moulds. The positions of the ejector pins are often determined by the installation space in the mould frame, which is restricted by temperature control, guides, and the component's geometry. Additional material often has to be designed into the component in order to define a position for the ejector, which is contrary to the lightweight construction potential. In order to solve these and other problems associated with conventional demoulding systems, there is a need for alternative demoulding concepts that do not use ejector pins, especially with respect to very thin-walled castings.

2. Preliminary Investigations

The high-pressure die-casting process has some harsh conditions that distinguish it from other common production or part-handling tasks. These conditions and the usable materials must be determined in the first step. The aim of the preliminary tests is, on the one hand, to investigate the suitability of the selected suction pad concepts to fulfil the requirements of the HPDC process. On the other hand, the possible vacuums and the maximum holding forces are determined. This is essential for designing the system and calculating the possible holding and demoulding forces.

2.1. Boundary Conditions of the Application

The main factor influencing the demoulding system is the temperature of the casting shortly before demoulding. The temperature varies locally on the casting and can reach up to 400 °C in some cases [7]. Due to thermomechanical fatigue, cracks form on the mould surface with increasing mould age until the mould fails. This failure leads to the formation of burrs on the casting, which become more distinctive over time [8]. The surface condition is another factor to be considered, as well as the release of agent residues or other process additives that can adhere to the casting after the mould has been opened. In addition, the angle at which the subsequent demoulding force is applied to the contact surface should be taken into account.

2.2. Material Selection

Elastomers are typically used as suction pads. Depending on the area of application, different elastomers offer different levels of resistance in addition to their elastic deformability. They offer sufficient flexibility and good resistance to many media; for example, FFKM offers good chemical resistance to most media such as lubricating or fuel oils, acids, bases, alcohols, and hydrocarbons. Fluoroelastomers such as FKM or FFKM are suitable for handling in the high temperature range. Fluoroelastomers can withstand limited exposure to 300 °C. However, they should not be exposed to temperatures higher than 315 °C, as HF emissions can occur [9].

To avoid this risk and to guarantee performance up to 400 °C, a suction pad made of an elastomer with a heat barrier and an aramid felt covering the surface was used (Figure 1). As a result, application temperatures of 400 °C during operation and peaks of up to 500 °C were realised [10]. When vulcanising the elastomer, the back of the suction pad can be connected directly to a metal support body, e.g., aluminium, which is relevant with regard to the development of a contoured mask, as shown later.

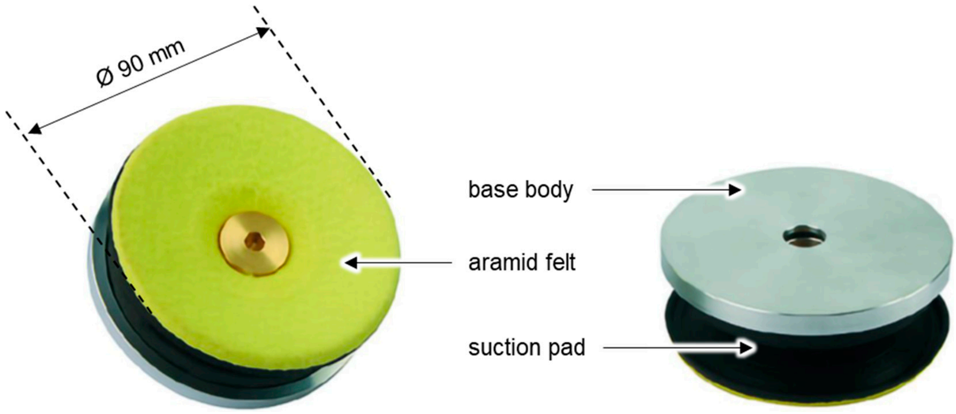
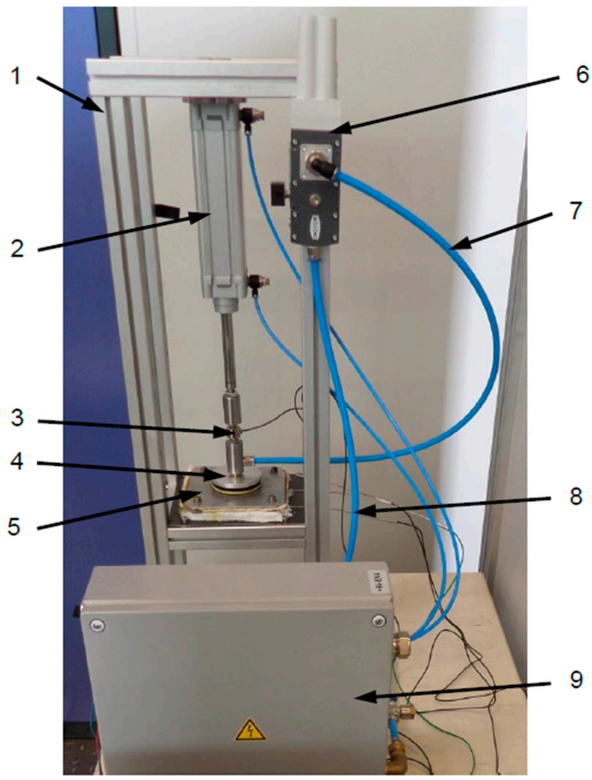


Figure 1. Structure of the vacuum cup used in the preliminary tests.

2.3. Experimental Setup and Test Procedure

The test rig is set up as shown in Figure 2 to determine the vacuums and the maximum holding forces, taking into account the process-relevant boundary conditions. The test rig essentially consists of the base frame (1), the vacuum ejector (2) with an integrated vacuum sensor, a linear unit (2), the test plate (5) and the force sensor (3). The vacuum ejector provides the required vacuum at the suction pad, and enables a maximum flow rate of 300 L/min and a maximum vacuum of 90%. The linear unit applies the required tear-off force, which is detected by the force sensor. An aluminium die-cast plate and segments from a real die-cast component, which can be heated up to 400 °C using an electric heating element and a mounting with a changeable angle, are used as test plates.



1—Base frame
2—Pneumatic cylinder
3—Force sensor
4—Vacuum suction cup
5—Heated plate
6—Vacuum ejector
7—Vacuum suction tube
8—Compressed air tube
9—Control unit

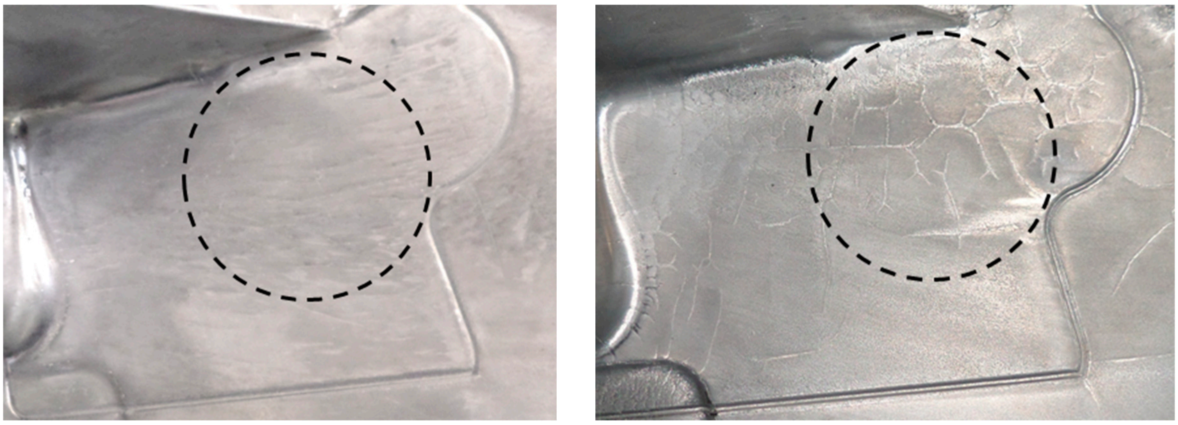
Figure 2. Setup of the test rig.

The following variables for the preliminary tests are derived from the boundary conditions mentioned in Section 2.1 of the application:

- Temperature: RT, 100 °C, 200 °C, 300 °C, 400 °C;

- Angle 0°, 5°, 10°, 15° (at all temperatures);
- Lubricant Chem-Tend SL 67867A (at 200 °C) (Chem-Trend, Maisach, Germany);
- Surface roughness/burrs after mould age of 19 k and 115 k cycles (at 200 °C).

To analyse the effect of a rough surface, particularly from burrs due to the ageing of the casting moulds, segments from a real die-cast component were used. The segments shown in Figure 3 were taken from the area near the runner of a shock tower from a passenger car. For all other tests, the aluminium die-cast plate with a smooth surface was used. The surface corresponded to a new mould with 500 cycles.



(**a**) (**b**)

Figure 3. Segments taken of a shock tower out of a mould with different ages and positions of the suction cups indicated by dotted circles: (**a**) casting from a mould after 19,000 cycles; (**b**) casting from a mould after 115,000 cycles.

The following procedure was used to realise the experiment:

- Setting the required temperature and angle;
- Moving the suction pad onto the test plate;
- Switching on the vacuum and depressurising the linear unit;
- Suctioning until maximum vacuum was reached;
- Applying the pull-off force by the linear unit at approx. 120 N/s;
- Ending when the suction pad was released from the plate.

2.4. Results of the Preliminary Investigations

As the vacuum and the effective area of the suction cup can vary during the test, the maximum pull-off force before detachment occurs is defined as the target value. Each test was carried out at least seven times and the mean value and standard deviation were taken into account for the evaluation. Figure 4 shows the mean value and standard deviation of the maximum holding force as a function of temperature and pull-off angle.

The maximum holding forces can be achieved at a pull-off angle of 0° and decrease as the angle is increased. The results are plausible, as the pull-off force is divided into a normal force to the surface and a shear force when the angle is increased. Assuming that the force is divided into normal and shear force at an angle of 15°, the diagram shows that the difference between the calculated and measured force deviates. This shows that the force distribution of classical mechanics cannot be applied here and that the behaviour is much more complex and must be taken into account in the subsequent design. The behaviour with an increase in temperature is striking. The pull-off force increases with increasing temperature in each series of tests.

If the maximum achievable vacuum is also considered, it can be seen that, at room temperature (RT), only 72.6% vacuum can be achieved. At 100 °C, it increases to 75.0%, and at 200 °C, it reaches 76.5%. From 300 °C, it stagnates at 78.8% and at 400 °C at 78.9%. This trend occurs at all angles.

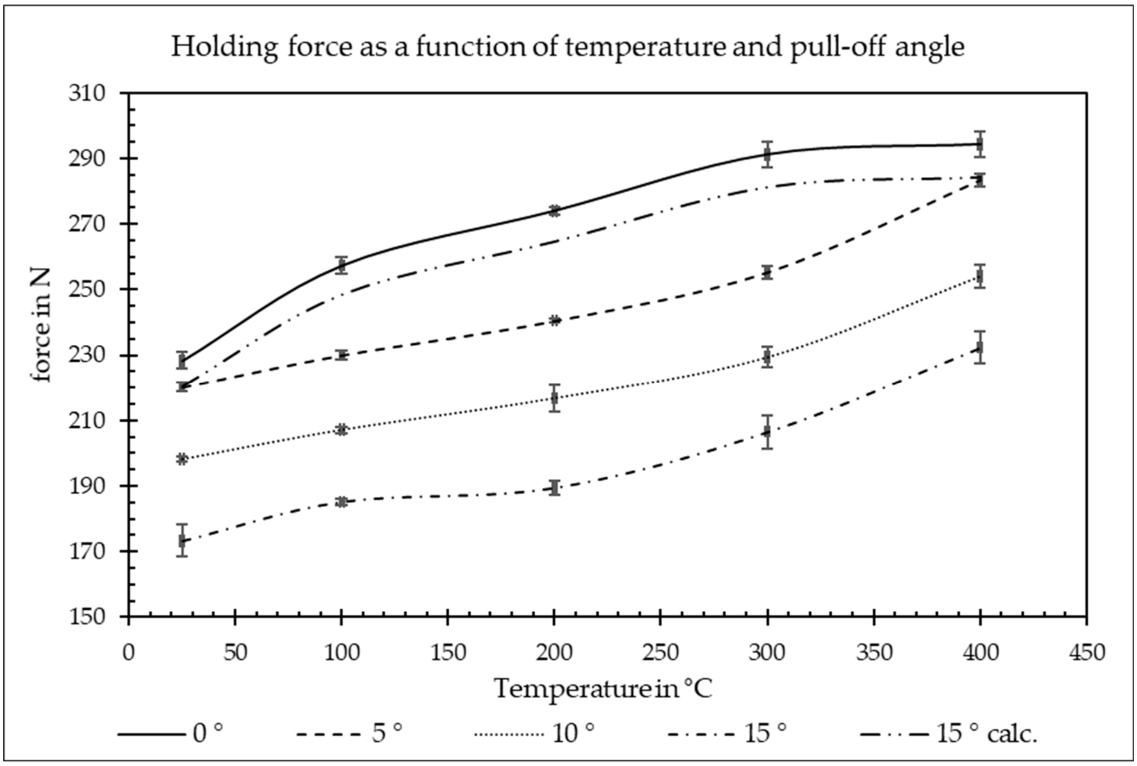


Figure 4. Mean value and standard deviation of the maximum holding force as a function of temperature and pull-off angle.

An explanation for the rise in the holding force and vacuum when the temperature is increased may be that, in the present form, there is a random structure to the fibres in the felt and in the properties of the aromatic polyamide (see also [11,12]). The aromatic polyamide has a negative coefficient of thermal expansion and a decrease in Young's modulus when the temperature increases. When the temperature increases, the fibres become more flexible and contract due to the negative coefficient of expansion. This means that the randomised felt structure becomes denser on the one hand and has higher elasticity on the other. This leads to a better seal on the surface, which results in a higher vacuum and lower permeation. Again, the higher vacuum and lower permeation results in a higher holding force.

To compare the effects of release agent residues on the mould surface and mould ageing, tests were carried out at 200 °C at an angle of 0°. The test with the smooth aluminium plate from Figure 4 was taken as a reference. Table 1 shows the maximum holding force. It is remarkable that neither the release agent nor the burrs have a strong influence on the holding force.

Table 1. Maximum holding force at 200 °C influenced by release agent and mould ageing.

	Reference	**With Lubricant**	**19 k Cycles**	**115 k Cycles**
Mean	274.0 N	277.9 N	271.3 N	271.0 N
Standard deviation	1.2	1.8	0.7	1.8

The sealing area of the suction pad is always subject to permeation, i.e., air is continuously extracted during handling. The moisture present, or, in this case, the release agent residue, is sucked away directly and does not have a negative effect.

The following explanation can be given with regard to castings from an aged mould. Due to the random structure of the felt, the individual fibres can adapt well to the surface texture, such as burrs. This also results in no reduction in the holding force.

In summary, the selected vacuum gripper concept and material are suitable. The most important influencing process factors such as temperature, release agent, and surface ageing of the mould were examined and showed no negative influence on performance. Increasing the temperature increased the possible holding force. When designing a contoured vacuum mask, this should be taken into account to the effect that the design should be based on the lowest temperature that could occur.

When designing the mould, however, it should be also considered that sealing surfaces should be selected as close to the pull-out direction as possible. The greater the pull-off angle, the greater the reduction in the possible holding force.

3. Methods

3.1. Calculation of the Shrink-On and Performance of the Demoulding System

In order to be able to demould the casting, the following equation must be fulfilled:

$$F_{Demoulding} \geq F_{shrinkage} + F_{adhesion} \quad (1)$$

With increasing casting complexity, the manual calculation of shrinkage is no longer feasible. The MAGMASOFT 6.0 casting simulation software offers a module that can be used to calculate the shrinkage of the casting onto the mould, the resulting contact pressure, and, taking into account static and dynamic friction coefficients, the demoulding of the casting using ejector pins.

In conventional ejector systems, the force for demoulding is applied via a hydraulic cylinder that is connected to an ejector plate, which, in turn, contains ejector pins that transfer the force to the component at specific points. In the present case, the holding force of the vacuum system is at least equal to the ejector force $F_{Demoulding}$.

$$F_{holding} \geq F_{Demoulding} \quad (2)$$

The holding force of the vacuum suction cup can be determined as follows:

$$F_{holding} = (p_{ambient} - p_{vacuum}) \times A \quad (3)$$

The pressures $p_{ambient}$ and p_{vacuum} are to be used as absolute pressures. A is the effective area of the interior of the suction pad. A general parameter for the effectiveness of vacuum cups is the contact pressure σ. This is calculated using the following equation:

$$\sigma = \frac{F_{holding} - m(g + a)}{A} \quad (4)$$

Most suction cups have a certain amount of leakage between the sealing element and the workpiece; this is called permeation. It is decisive for the maximum achievable vacuum and the required power of the system. This is calculated using the following equation:

$$\dot{V} = \frac{\delta V}{\delta t} = \frac{P}{\sigma} \quad (5)$$

3.2. Simulation of the Ejection Process

The MAGMASOFT 6.0 casting process simulation software is used to estimate the required demoulding force. In addition to the calculation of mould filling and solidification via FDM, the software can also be used to calculate the demoulding force with conventional ejector pins. MAGMASOFT 6.0 calculates the resulting contact pressures between the casting and mould during solidification. This stress state is transferred to the following FEM in MAGMASOFT 6.0. Meshing and mapping from FDM to FEM is, however, a black box of the software. The casting is pushed out of the mould using the ejectors. In the so-called evaluation areas between the casting and the ejector, the contact pressures are logged during the demoulding process and the force occurring in the ejector is calculated via the existing surface of the ejector. Summing up the forces results in a force–time curve of the ejector force.

In contrast to pushing the casting out of the ejector side of the mould using ejectors, demoulding using suction pads was carried out by pulling on the other side of the casting. The direct modelling of demoulding using suction pads was not implemented, which is why the following substitute model was created (see Figure 5). Ejectors are placed on the ejector side in the central area of the individual suction segments, with which the casting is demoulded.

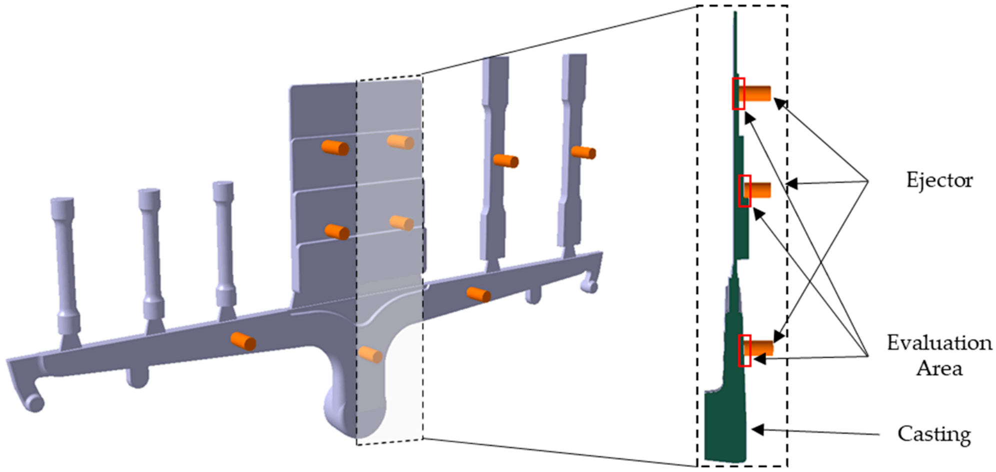


Figure 5. Geometric setup of the simulation of the demoulding process in MAGMASOFT with the ejector pins placed in the central area of the individual suction segments. The evaluation surface between the casting and the ejector is marked in the cross-section.

The demoulding process in MAGMASOFT 6.0 is calculated under the steady-state thermal condition of the casting process. The main parameters of the simulation are shown in Table 2.

Table 2. Main parameters of the casting simulation and calculation of the demoulding process.

General Parameters			
Alloy	**Melt temperature**	**Mould temperature**	**Cycle time**
AlSi10MnMg	680 °C	200 °C	82 s
Ejection parameters			
Element size	**Friction coefficient**	**Duration**	**Stroke**
2 mm	0.2	2.0 s	5 mm

3.3. Design of the Demoulding System

The contour-adapted vacuum felt suction cups should have the properties of the standard felt suction cups as far as possible. The aim is to create a segmented suction mask that has sealing surfaces adapted to the contour of the casting. The geometry of the sealing surfaces of the contour suction cups is initially limited to two-dimensional areas of the casting.

In co-operation with Werner Vakuumsauger GmbH from Meckenheim Germany, a manufacturing strategy for the production of the individual segments is being developed. The concept has the structure shown in Figure 6. The sealing felt (1), the flexible layer (2), the mounting plate (3), and the seal (4) are vulcanised together. For the vulcanisation process, which creates a bond between the silicone and the felt, the felt and mounting plate are placed in a prefabricated mould and encapsulated with a temperature-resistant silicone and vulcanised. This creates a material bond between the components.

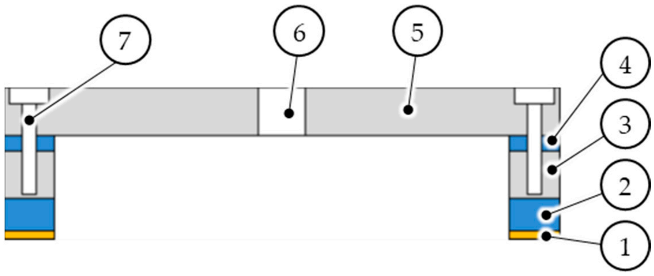
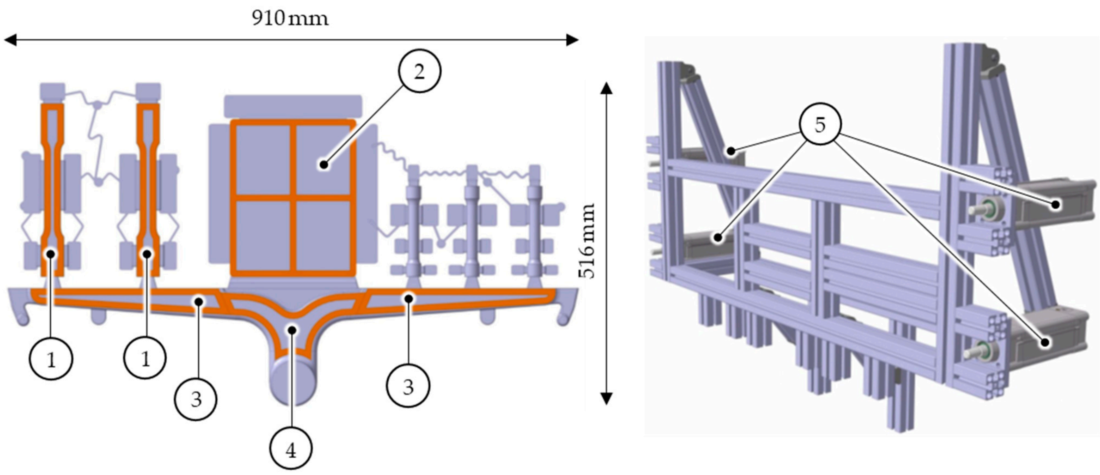


Figure 6. Basic structure of the developed contour suction cups.

The carrier plate (5), which has holes for the suction line and sensor connections (6), is mounted to the mounting plate using screw connections (7). The unit, consisting of the seal, the mounting plate, the flexible layer, and the sealing felt, is referred to below as the contour seal.

In order to determine the necessary width of the contour seal, the manufacturer of the vacuum cups is consulted and the effective suction area is estimated from the preliminary investigations. This is for estimation purposes only and assumes the same vacuum distribution in the non-contact area. It only applies to the present case. Suction pads have a contact and a non-contact area (see also [13]). This means that even flexible suction pads only have contact with the workpiece to be handled in the outer area. The smallest non-contact area and its diameter are thus calculated for the most conservative case from the measured pressures and holding forces of the suction pad in the preliminary test. At room temperature, a minimum holding force of 228.3 N was achieved with a 72.6% vacuum. This corresponds to an area of 3144.6 mm^2 with an effective diameter of 63.3 mm. The effective sealing width is, therefore, 13.4 mm. This is in line with the manufacturer's statement that a sealing width of at least 15 mm should be taken into account. For the development of the segmented vacuum mask, the contour seal is set at 15 mm, so that a safety factor of approx. 12% is taken into account in the design.

A test mould is available as a die-casting tool, which also has a conventional ejector system as a backup solution. The casting and the sealing surfaces applied to it are shown in Figure 7a. The casting consists of a runner system, which is covered by two segments, (3) and (4); two tensile specimens (1); one casting plate (2); and three fatigue specimens, which are excluded due to their curvature. The contour-adapted vacuum felt suction cups are mounted on a carrying frame, as shown in Figure 7b. The demoulding force is applied via four pneumatic cylinders, which can apply a maximum of 11,222 N at a pressure of 9 bar.



(**a**) (**b**)

Figure 7. (**a**) Segments of the vacuum suction mask and sealing surfaces (orange). (**b**) Carrying frame for the suction mask with four pneumatic cylinders (5).

The achievable holding force of the vacuum mask for connecting the casting and the removal device is calculated using the inner surfaces of the contour-matched suction surfaces at 70% vacuum. This results in a total holding force of 3922 N (see Table 3).

Table 3. Inner surfaces of the contour-matched suction areas with calculated holding forces at 70% vacuum.

No.	Description	Quantity	Single Area [mm^2]	Holding Force Single Area [N]	Holding Force Sum [N]
1	Tensile specimen	2	2520	179.7	359.4
2	Plate segment	4	9490	672.8	2691.2
3	Runner, arm	2	3560	252.4	504.8
4	Runner, divider	1	5170	366.6	366.6
			Total holding force		**3922**

3.4. Experimental Setup at the Die-Casting Machine

The complete structure of the removal device (6) is attached to an industrial robot (2) of the type KUKA KR 180 R2500 extra, as shown in Figure 8. On the arm of the robot is a control cabinet (4) in which the sensors and valves for logging and switching the vacuum and pneumatic cylinders are located. The vacuum values and the pressures of the pneumatic cylinders are recorded in a separate data logger via the measuring cable (3). The vacuum is generated by the integrated vacuum system of the die-casting cell. This has a maximum flow rate of 2583.33 L/min, a vacuum tank with 1000 L, and a maximum achievable vacuum of 99%. The vacuum is generated by the integrated vacuum system of the Bühler Carat 140. The vacuum tank is connected to a distributor in the extraction device via a suction line (1). When dividing up the vacuum line, care is taken to ensure that the cross-sectional area does not have any narrow points, that friction losses in the air flow are minimised by the choice of geometry, and that the total cross-sectional area does not change when dividing up the line.

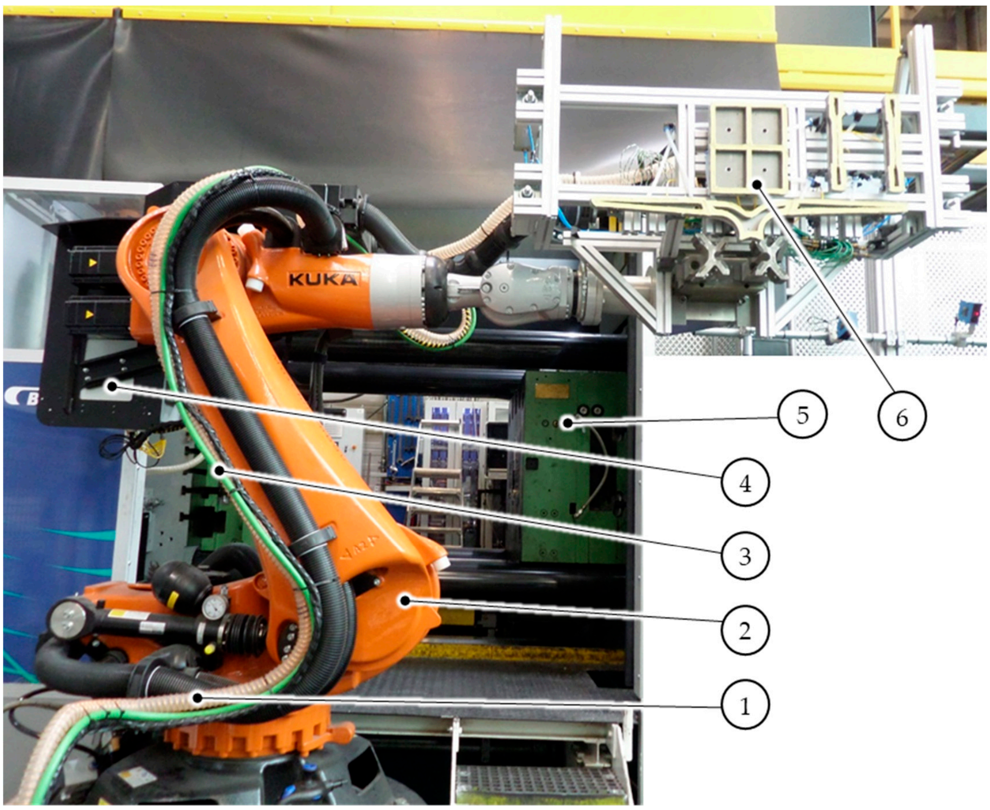


Figure 8. Experimental setup on die-casting machine with removal device (6) on industrial robot and the clamped mould in the background (5).

The trials were carried out on a Bühler Carat 140 high-pressure die-casting system, on which a fully automated and industry-oriented casting process was realised. In the casting process, an aluminium alloy of the type AlSi10MnMg with a melt temperature of 680 °C is used. The maximum pressure in the filling phase is 500 bar. The die-casting tool is tempered to 200 °C using tempering oil. After casting and mould opening, the removal process follows the following sequence:

- Robot moves to removal position;
- Vacuum on;
- Check vacuum > target value (75%);
- No -> Error and removal via ejector;
- Yes -> soft switching of robot axes -> enables vector move in demoulding direction;
- Pressurise pneumatic cylinder and wait until pressure is applied;
- Part is demoulded;
- Depressurise pneumatic cylinder;
- Remove part from moulding area;
- Place on component lock and switch off vacuum.

4. Results and Discussion

4.1. Simulation of the Ejection via Pins

The curve of the calculated demoulding force was plotted over the process time, as shown in Figure 9. Two local maxima occur during the process. The first occurs during the mould-opening process, in which the cover die is removed in the simulation. During the process, the casting undergoes a small reversible deformation, which leads to a small increase in the forces that act on the ejector pin. From 75.0 s, the demoulding process takes place, during which the force rises abruptly to 1782.5 N within 0.3 s. Within this short period of time, the static friction is overcome in most areas of the casting. In the further course of the process, the casting is ejected when the sliding friction is overcome and reaches its maximum force of 1952.2 N.

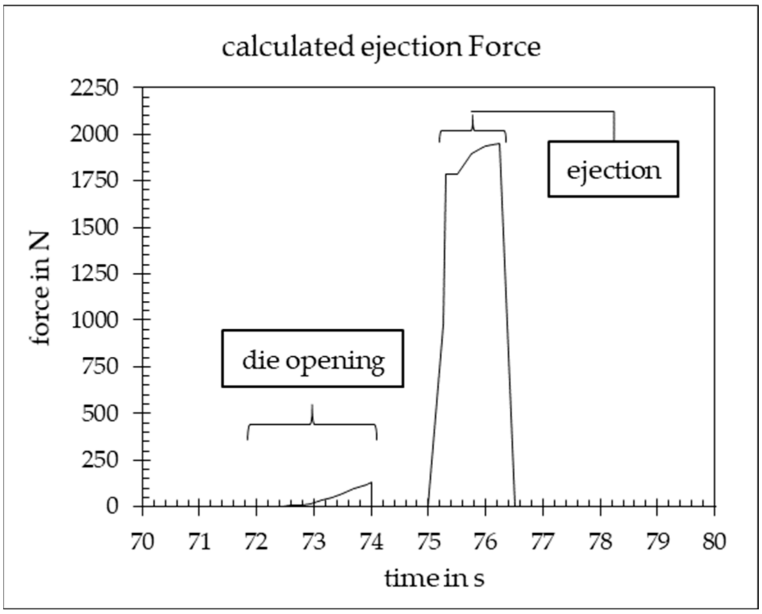


Figure 9. Calculated demoulding force with marking of the process phases. During ejection, there are locally different conditions with regard to static and dynamic friction.

At first look, the curve does not correspond to expectations. With an ideal cylindrical or cuboid body and a uniformly distributed application of force, the demoulding force would initially rise to a global maximum and, after overcoming static friction and switching to sliding friction, would run on a lower plateau that decreases with time until complete demoulding.

This deviation from the ideal can be explained as follows. On the one hand, the casting does not have an ideal cylindrical or cuboid geometry and the demoulding force is not evenly distributed over the component. When looking at Figure 5 in Section 3.2, it can be seen that the force application points or ejectors are increasingly on the side of the tensile specimen and that there are also geometries in the outer area of the barrel that favour clamping. This leads to the static friction being overcome locally at different times and to the casting tilting or jamming with the mould during the sliding process, which, in turn, leads to a further increase in force.

All in all, the calculated maximum demoulding force of 1952 N is below the achievable holding force of 3922 N, thus fulfilling the condition from Equation (2) in Section 3.1. In terms of calculation, demoulding with the present new demoulding system is given for this casting.

4.2. Demoulding Process

The experimental implementation on the die-casting machine in the fully automated casting process was successfully implemented. Demoulding using the segmented vacuum mask worked. Figure 10 shows the measured pressures of the four grouped segments: (1) tensile specimen, (2) plate segment, (3) runner, arm, and (4) runner, divider, and the total demoulding force applied calculated from the pressure and effective areas of the four pneumatic cylinders.

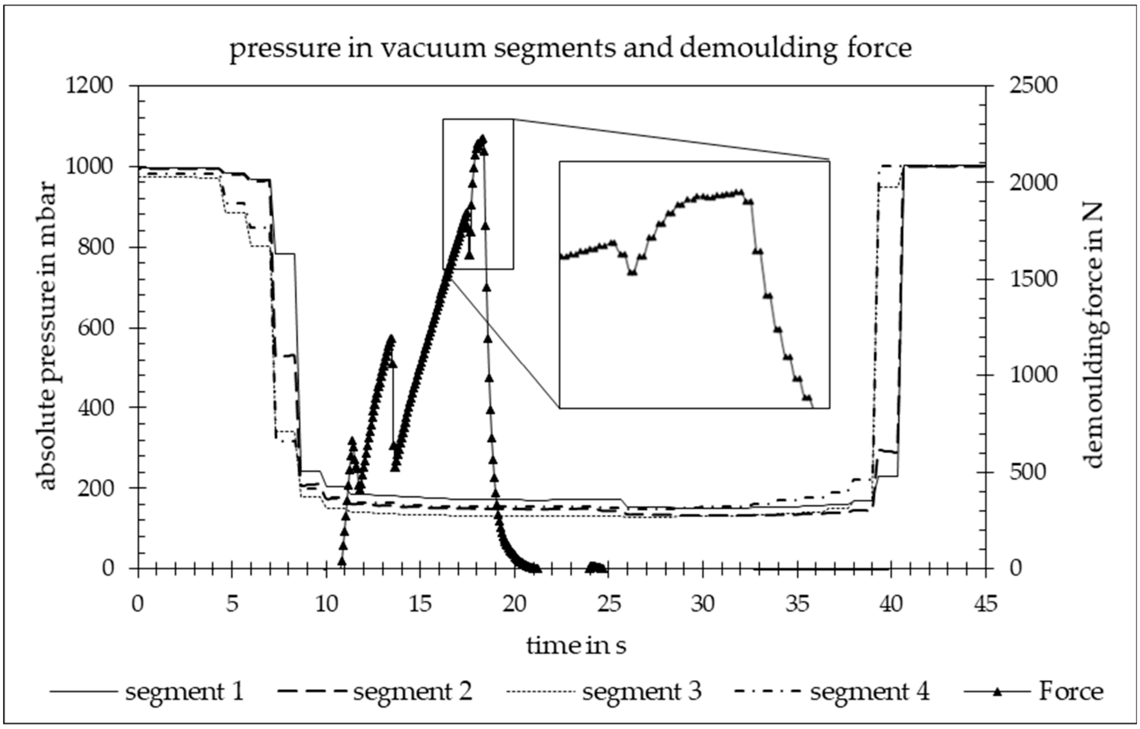


Figure 10. Measured pressure in the grouped vacuum segments and demoulding forces of the experimental investigation in the die-casting process for a representative cycle. The time is from the beginning of the demoulding phase to placement on the sluice. The highlighted area shows the process during the actual demoulding.

The pressure build-up in the cylinders takes approx. 6 s until the actual demoulding begins. During this process, local minima occur at 11.5 s and 13.5 s, which can be explained by the stick–slip effect. The stick–slip effect occurs when the static friction is significantly greater than the sliding friction. The rod seal and the piston seal on the pneumatic cylinder create a comparatively strong static and sliding friction [14].

The actual demoulding process is shown in the highlighted area in Figure 10. The local minimum in the highlighted area is the short pressure drop at which the static friction is overcome. This exhibits the same behaviour as described in the simulation. As a result, the casting is pulled out of the mould and, as seen in the simulation, is subject to jamming and slight tilting. A total force of 2228.2 N was applied to demould the casting.

The vacuum is above the required target value of 75% or below 250 mbar in all groups and, during the demoulding process, it is well above the maximum vacuum value of 78.9% determined in basic tests. The vacuum curves are continuous, without local minima, which is an indication that the suction segments do not lift off the casting. The maximum vacuum values in the four grouped segments are 86.4% in the tensile specimen (1), 88.2% in the plate segment (2), 88.7% in the runner, arm (3), and 86.6% in the runner, divider (4).

Three aspects have been identified as the cause of the discrepancy between the preliminary test and the trials in the casting process and are discussed below. The first aspect concerns the vacuum supply. In relation to the effective area of the suction cup, the ejector in the preliminary test provides approx. 0.10 L/min per 1 mm^2 at a maximum vacuum of 90%. The vacuum pump and the tank of the casting system provide a similar suction capacity of 0.12 L/min per 1 mm^2, but they enable a vacuum of 99% from the tank. This can be used to compensate for possible leaks in the suction line system.

The second aspect is the pressing of the suction cup onto the substrate. In the preliminary test, the contact pressure was based solely on the weight of the suction cup, connecting parts, and piston with piston rod. The output of the axis torques of the robot showed 1130 Nm for the axis with which the part was pressed on, with a lever of 2.59 m; this corresponds to a contact force of 436 N.

The third aspect is the temperature of the casting before removal. For this purpose, the temperature of the casting was measured tactilely in the areas of the segments after the part had been ejected and deposited. These values are shown in Table 4 and were recorded after 40 s, as illustrated in Figure 10.

Table 4. Measured temperature of the casting after extraction and transfer out of the casting cell.

No.	Temperature in °C				
	Top Plate	**Bottom Plate**	**Tensile Specimen**	**Runner, Arm**	**Runner, Divider**
1	210	320	280	320	380
2	230	340	305	340	375
3	235	350	315	365	395
4	215	320	290	325	345
5	225	335	310	320	370
6	220	330	300	325	340
7	220	330	300	320	355
Mean	**222**	**332**	**300**	**331**	**366**
Standard deviation	**8.0**	**9.9**	**11.0**	**15.5**	**18.4**

The temperatures in the divider of the runner reach their maximum values in the peak up to 395 °C, while the coolest areas are in the upper part of the plate with a min. of 210 °C. On average, the temperatures measured are mainly between 300 and 360 °C. Due to the time elapsed between suction and deposition, it can be assumed that the parts are slightly hotter at the start of the demoulding process. The temperatures of the parts are all within the range of the maximum vacuum of the preliminary tests, with the exception of those in the top of the plate. The analysis of the temperatures shows that the prerequisite for a maximum achievable vacuum is given here, but is not the cause of the higher values compared to the preliminary tests. It can be assumed that the combination of take-off angle, temperature, and volume flow provides ideal conditions and that the pressure and the high available vacuum decisively improve the vacuum.

4.3. Further Discussion

The demoulding forces measured in the experiment are approx. 15% higher than those in the simulation. The prediction of the necessary forces using MAGMASOFT 6.0 can initially be rated as good. The discrepancy in the results can be explained on the one hand by the high dynamics and the extreme boundary conditions of the die-casting process, and on the other hand by the modelling of the demoulding process using ejector pins. The basic behaviour during demoulding with static and sliding friction as well as jamming can be observed in both the simulation and experiment.

The feasibility of a vacuum extraction system based on a two-dimensionally contoured mask has been demonstrated. The next step is to increase the geometric complexity and, thus, adapt it to a three-dimensional contour. In particular, the manufacturing process of the contour seal with Werner vacuum cups must be determined and its limits identified.

A further research approach is the investigation of the sealing width and its influence on achievable vacuums and holding forces, as the vacuum mask, in contrast to conventional round or rectangular suction pads, only has a contour seal and no variable flexible seal over the entire area. Existing investigations such as [15,16] can be consulted for this purpose.

With regard to large-area structural parts, the influence of the system on the distortion of the cast part due to demoulding can be investigated in contrast to conventional demoulding systems based on ejector pins. The extent to which the uniform application of negative pressure to a large area can be advantageous compared to the punctual force transmission of pins must be examined.

If the internal ejector system can be completely dispensed with in moulds, this opens up further degrees of freedom in terms of mould design. On the one hand, far-reaching possibilities are conceivable in the design of the cooling process, such as mask cooling [17,18], or, on the other hand, greater stability of the mould can be achieved.

5. Conclusions

This paper shows the development and successful implementation of an alternative demoulding system for the die-casting process. The basis is the calculation of the necessary force on the one hand and the performance of the demoulding system on the other.

A suitable material concept is identified in the preliminary investigations and its performance capability is analysed, taking into account the application-specific requirements. The suction pads are made of an elastomer with a thermal barrier and the surface is covered with an aramid felt. This enables application temperatures of 400 °C during operation and peak values of up to 500 °C.

MAGMASOFT 6.0 was used to set up an equivalent model and estimate the shrinkage force. Together with the calculation of the possible holding and demoulding force, a segmented vacuum mask for the removal system was developed, built, and successfully tested in the die-casting process. Higher performance was achieved with regard to the achievable vacuums of up to 88.7%.

6. Patents

EP4168194-VACUUM MASK, DEVICE AND METHOD FOR DEMOLDING A CAST PART.

Author Contributions: Conceptualisation, methodology, A.H.; simulation and preliminary tests, A.H. and A.S.; writing—original draft preparation, A.H.; writing—review and editing, A.S. and S.F.K.; supervision, M.F.; technical execution of experiments on the die-casting machine, T.K. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the "Industry Promoting Group" of the Department of Foundry Technology as part of a pre-competitive and independent collaborative research project.

Data Availability Statement: The original contributions presented in the study are included in the article. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Lehmhus, D. Advances in Metal Casting Technology: A Review of State of the Art, Challenges and Trends—Part I: Changing Markets, Changing Products. *Metals* **2022**, *12*, 1959. [CrossRef]
2. Musk, E. Battery Day Presentation, 2020 Annual Meeting of Stockholders and Battery Day, 22 September 2020. Available online: https://digitalassets.tesla.com/tesla-contents/image/upload/IR/2020-battery-day-presentation-deck (accessed on 15 May 2024).
3. Volvo Mega-Casting. Available online: https://www.media.volvocars.com/at/de-at/media/photos/294343/volvo-mega-casting-1 (accessed on 17 May 2024).
4. Wärmefjord, K.; Hansen, J.; Söderberg, R. Challenges in Geometry Assurance of Megacasting in the Automotive Industry. *J. Comput. Inf. Sci. Eng.* **2023**, *23*, 060801. [CrossRef]
5. Nogowizin, B. *Theorie und Praxis des Druckguss*; Schiele & Schön: Berlin, Germany, 2010; pp. 643–644.
6. Krischke, S.; Müller, S.; Schuchardt, T.; Kouki, Y.; Dilger, K. Experimental Investigations on the Ejector Forces in the Die Casting Process. *Arch. Foundry Eng.* **2018**, *18*, 116–119. [CrossRef]
7. Gebauer-Teichmann, A.; Herzog, R.; Egner-Walter, A.; Hepp, E.; Enselmann, A.; Garcia- Sobolevski, E.; Gibmeier, J.; Scholtes, B. *BMBF Schlussbericht Fertigungsoptimierung Dünnwandiger Gussteile aus Leichtmetall*; Funding-Nr 02PD2140; Technical Information Library Hannover: Hannover, Germany, 2005. [CrossRef]
8. Klobčar, D.; Kosec, L.; Kosec, B.; Tušek, J. Thermo fatigue cracking of die casting dies. *Eng. Fail. Anal.* **2012**, *20*, 43–53. [CrossRef]
9. Ferrandez, P. Fluoroelastomers, FKM and FEPM. In *Handbook of Specialty Elastomers*, 1st ed.; Klingender, R.C., Ed.; Taylor & Francis Inc.: New Delhi, India, 2008; pp. 133–137.
10. Werner Vakuumsauger GmbH. Hochtemperatursauger. Available online: https://werner-vakuumsauger.de/produkte-vakuumsauger-gummiformteile/#hochtemperatursauger (accessed on 17 May 2024).
11. Yang, H. *Kevlar Aramid Fiber*; John Wiley & Sons: Chichester, UK, 1993; pp. 37–40. ISBN 0-471-93765-7.
12. Lacks, D.; Rutledge, G. Thermal expansion and temperature dependence of elastic moduli if aromatic Polyamides. *Macromolecules* **1994**, *27*, 7197–7204. [CrossRef]
13. Tiwari, A.; Persson, B. Physics of suction cups. *Soft Matter* **2019**, *15*, 9482–9499. [CrossRef] [PubMed]
14. SFS-Fluidsysteme GmbH. Smooth-Running Cylinders and Seal-Less Cylinders. Available online: https://sfs-fluidsysteme.com/en/smooth-running-cylinders-and-seal-less-cylinders/#:~:text=The%20stick-slip%20effect%20always,occurs%20on%20the%20pneumatic%20cylinder (accessed on 18 May 2024).
15. Hudoklin, J.; Seo, S.; Kang, M. Vacuum Suction Cup Modeling for Evaluation of Sealing and Real-Time Simulation. *IEEE Robot. Autom. Lett.* **2022**, *7*, 3616–3623. [CrossRef]
16. Guo, B.; Zhang, B.; Fang, S.; Yang, L.; Zhang, A. *The Study of the Effective Contact Area of Suction Cup*; SAE Technical Paper, 2021-01-0298; SAE: Warrendale, PA, USA, 2021. [CrossRef]
17. Haban, A.; Fehlbier, M.; Reiche, L. Implementation of an intermittent spray cooling for die casting tools in the series process. In *Casting of Chassis and Body Components*; VDI Reports, 2367; VDI Wissensforum GmbH: Bad Gögging, Germany, 2020; pp. 131–139.
18. Reiche, L. Entwicklung einer Geregelten und Energieeffizienten Werkzeugtemperierung im Dauerformguss unter Einsatz einer Sprühkühlung mit Wärmerückgewinnung. Ph.D. Thesis, Universität Kassel, Kassel, Germany, 2019. [CrossRef]