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INCREASING THE WELDABILITY OF DIE CAST PARTS BY MINIMAL DIE LUBRICATION

(Ch. Garthoff, H. Pries, K. Dilger)
Institut of joining and welding, University of Technology Braunschweig, Braunschweig, Germany
(D. Tomazic)
Chem-Trend (Deutschland) GmbH, Norderstedt, Germany

ABSTRACT

The lubrication of the die is one of the key parameters of the high-pressure die casting process, as it has a great influence on the process stability and the properties of the cast parts.
Along with the surface condition, release agents have an influence on the porosity of die casting parts, as they have to be seen as a hydrogen source. This is especially important when the die-cast parts are to be welded or heat treatment is applied.
To meet these requirements a process for applying minimal amounts of release agent and corresponding release agents was tested.
Aim of this development is the reduction of the amount of hydrogen contamination by applying only small amounts of release agent concentrate.
Another positive effect is to be seen in a significantly reduced thermal stress of the die, as the temperature drops are reduced by applying minimal amounts of release agent concentrate. This offers the possibility of increasing the lifetime of the die.
In a first step the conventional spraying process was optimized, focusing on minimum porosity after welding. The results of these test trials are used as a reference to evaluate the new micro spraying process. Assessment criteria were the carbon layer thickness (measured by EPMA), corrosion behavior and the porosity before and after welding. To determine the differences of temperature transfers between the micro spraying process and conventional die lubrication, time-dependent temperature profiles were measured on a test stand.

Keywords: High-pressure die casting, die lubrication, welding, porosity, release agent application

INTRODUCTION

The possibility of producing parts of a complex geometry in low cycle times leads to the establishment of the high-pressure die casting of aluminum alloys as import process in the industrial production, especially in the automotive industry.
Against the background of increasing demands concerning the weight reduction in order to increase the fuel savings, lightweight design structures based on aluminum are to be seen as one important solution. To keep the costs of production at a low level efficient production processes are required, e.g. high-pressure die casting. Furthermore, the demands for solid and safe joints have to be fulfilled. This requirement can be achieved by using welding processes. So the approach of building lightweight structures by welding die cast parts, results in the necessity of realizing weldable die cast parts. In several research projects carried out at the ifs the weldability of die cast parts could be realized and improved.
In this research work the content of dissolved gases and release agent residuals were identified as important factors influencing the weldability of die cast parts. As the influence of the release agent on the contamination of the surface with organic substances can be directly deduced, the indirect influence has also to be considered. The thermal decomposition of the release agent induced by contact with molten aluminum alloy leads to the deposition of hydrogen, forced into dilution while solidification by the applied pressure [1], [2], [3].
Apart from the influence of the release agent on the weldability of the cast parts, the release agent application also influences the life time of the die. So the release agents mainly used today are water-based and water-diluted for application. In the majority of the die spraying processes a significant temperature drop is induced, resulting in alternating stress and low-cycle fatigue [4].
To reduce the thermal shock, systems for applying minimal amounts of release agent concentrates were developed. As the use of these new release agent and application systems needs to be qualified for casting weldable parts, corresponding studies were conducted. These investigations include the casting of test pieces by using conventional and minimal die spraying, the analysis of the cast parts by using a re-melt test and electron probe

micro analysis. In addition, the temperature drop induced by die spraying was measured on a test stand, in each case for conventional and minimal release agent application.

DESIGN OF EXPERIMENTS

The investigations to evaluate the concept of minimal release agent application, the so-called micro spraying, were divided into two parts. The first part of the studies included the measurement of time-dependent temperature curves on a test stand. Motivation for these test trials was to identify the difference in the temperature drop, comparing conventional and minimal-amount die lubrication.
In the second part of the researches casting trials were conducted in the experimental foundry. Objective of these casting trials was the identification of release agent application parameters for the micro spraying approach suitable for die-cast weldable parts. Criteria for the evaluation of the cast parts were the formation of re-melt seams and the carbon layer thickness.

MEASUREMENT OF TIME-DEPENDENT TEMPERATURE PROFILES

To measure time-dependent temperature profiles according to the release agent application in the high-pressure die casting process, a test stand was designed and built at the TU-BS (ifs).
The main technical data of the test stand are listed below:

- heating power: 2 kW
- 16 thermocouples
- thermo wire Ø: 0.5 mm
- Typ K (Cr / CrNi)
- test body made from hot working steel X37CrMoV5-1 (1.2343)
- T_{max} > 400°C

In the picture of the CAD model of the test stand given in Figure 1, the positions of the thermocouples can be seen. The thermocouples are arranged in three depth levels (measured from the test stand surface): 1.5 mm, 3 mm and 4.5 mm. At each depth level there are 5 measuring points at the following distances from the center point:

- 10 mm
- 25 mm
- 40 mm
- 55 mm
- 70 mm

The center point itself represents a measuring point in a depth of 1.5 mm.

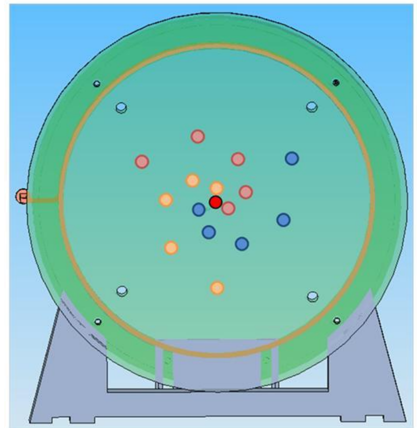
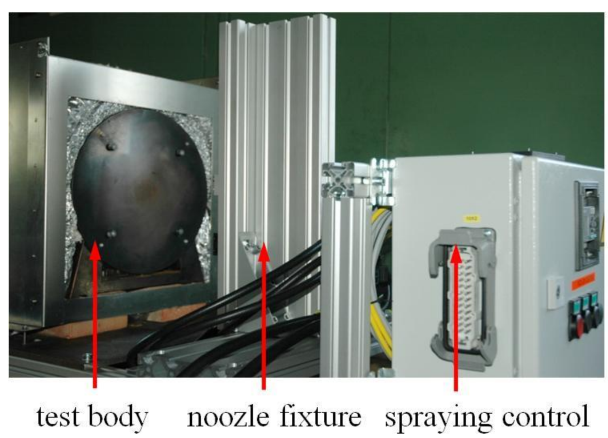


Fig. 1. Picture of the CAD model of the test body stand for measuring time-dependent temperature profiles

The buildup of the complete test as it was used to measure the temperature profiles can be seen in Figure 2. The test body containing the measuring points is housed in a thermal isolating box. The fixture of the nozzle is designed to gain a high degree of repeatability concerning the adjustment of the nozzle. The spraying control unit allows the implementation of die spraying programs equal to the spraying equipment in an experimental foundry. The test stand can be equipped with different nozzles corresponding to the demands for testing different die spraying systems. The release agent is filled into a pressure tank. Feed pressure and air pressure can be adjusted independently.



Fi g. 2. Picture of the test stand for measuring time-dependent temperature profiles

Key element of the tested minimal die lubrication is the nozzle. The so-called dosage nozzle is designed in a way that at each spraying impulse a small amount of release agent is fed into a chamber and applied, thus working discontinuously. So the amount of applied release agent is independent of the spraying time. On the contrary, the conventional nozzle provides a continuous release agent stream over the whole spraying time.

Temperature profiles (Experimental Design)

Before starting the main measurement aiming at obtaining the time-dependent temperature profiles, the repeatability of the measurements was checked in the case of chaining the nozzle. Therefore five trials were carried out with the following parameters:

- nozzle cap diameter: 0.6 mm
- air pressure: 5.5 mm
- feed pressure: 1.0 bar
- distance nozzle to surface: 134 mm
- start temperature. 250 °C
- spraying time: 0.5 s

The chosen parameters equal the application parameters to be used in following casting trials, except the spraying time which was set at 0.5 s to ensure the detection of short temporal occurrences. After each trial the nozzle was dismounted and then mounted and aligned again.
After these pre-tests the main trials were carried out. To detect differences in the temperature drop in dependency of the release agent application similar parameter sets were tested with the conventional and minimal-amount spraying nozzles. As the amount of applied release agent seems to be related to the feed pressure, so this parameter was also varied in the trials, with the aim of testing this dependence.
The defined start temperature of 250 °C represents a die temperature at normal casting conditions, whereas the high temperature of 390° C equals possible hot spots in the die.
An overview of the application parameter test in the trials for measuring time-dependent temperature profiles is given in Table 1. Using each parameter set, two trials were conducted.
To isolate the influence of the application system on the temperature drop from other parameters, water was used to test both nozzles. This allows a higher degree of comparability. A further argument for using water in these test trials is the fact that most conventional release agents used today are water-based and [5].
In addition to this, the newly developed release agent concentrates also are water-based.

Table 1. Overview test trials of measuring time-dependent temperature curves

Varied parameter		
Nozzle	**Start temperature**	**Feed pressure**
Conventional	250 °C	0.5 bar
		1.0 bar
		1.5 bar
	390 °C	0.5 bar
		1.0 bar
		1.5 bar
dosage	250 °C	0.5 bar
		1.0 bar
		1.5 bar
	390 °C	0.5 bar
		1.0 bar
		1.5 bar
Constant parameters		
Nozzle cap diameter:		0.6 mm
Air pressure:		5.5 bar
Distance nozzle to surface:		134 mm

Results (temperature profiles)

The analysis of the temperature profiles measured in the trials aiming to test the repeatability showed only slight differences between the five tests. Figure 3 shows the profiles of the five trials, recorded from the central measurement point (center of the spray stream, 1.5 mm below the surface). As regards the start temperature an average value of 250.31 °C could be achieved with a deviation of +/- 0.35 °C. With regard to the temperature minimum after spraying an average value of 215.95 °C was achieved with a deviation +/- 0.72 °C.

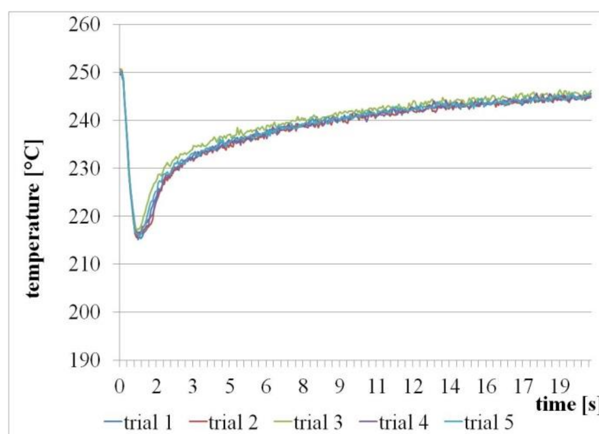


Fig. 3. Time-dependent temperature profile of the test measurements concerning the repeatability

To obtain a well-arranged overview respectively a comparison of the differences in the temperature drops according to the varied spraying parameters, the analyses were subdivided by temperature.
The characteristics of the temperature drops, starting at temperature of 250 °C are shown in Figure 4. Comparing the temperature profiles in dependency of the spraying nozzle, a significantly lower temperature difference emerges in the case of the dosage nozzle.

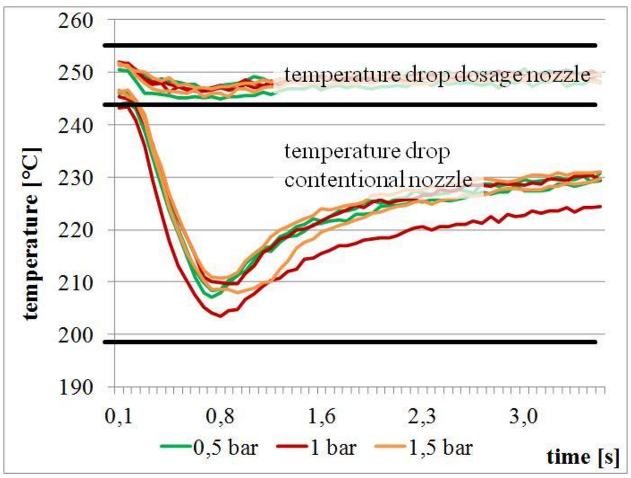


Fig. 4 Comparison of the time-dependent temperature profiles in the case of using conventional and dosage nozzles at a start temperature of 250 °C

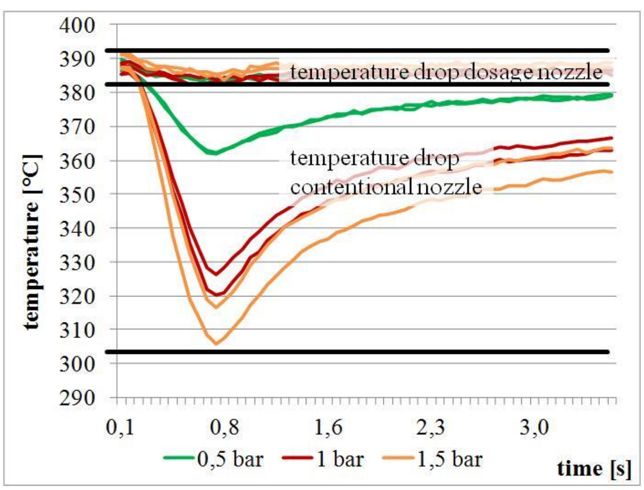


Fig. 5. Trends of the time-dependent temperature profiles in the case of using conventional and dosage nozzles at a start temperature of 390 °C

These significant differences in temperature drops in dependency of the applied spraying concept also occur in the case of the high start temperature of 390°C. This can be seen in the diagram given in Figure 5.

A summary of the measured temperature differences is given in Figure 6, which shows a comparative bar chart of achieved temperature differences at a start temperature of 250 °C.

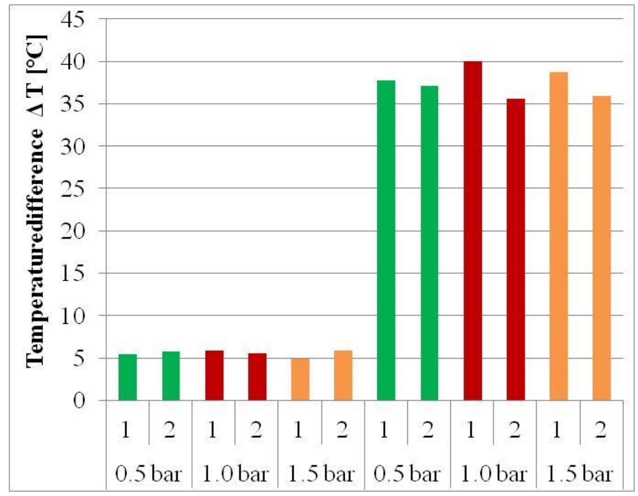


Fig. 6. Comparison of the temperature differences at 250 °C achieved by spraying with the dosage and conventional nozzles

The comparison of temperature differences determined by measurements starting at 390 °C is given in Figure 7.
As the estimated lower temperature drops in the case of the minimal die lubrication concept appear evidently at high and low start temperatures, whereas the influence of the feed pressure does not occur in such a clear way.
Looking at the temperature profiles recorded while spraying with the dosage nozzle, no influence on temperature by the feed pressure can by noticed. The only significant difference in the temperature profile trends occurs in the case of spraying on the surface with a temperature of 390 °C (see Fig.5, temperature drop conventional nozzle, green lines). Looking at the bar chart in Figure 8, the influence of the feed pressure on the conventional nozzle can be seen more clearly.
So the average temperature difference in the case of spraying with the conventional nozzle at 0.5 bar feed pressure has a value of 24.15 °C. The increase of the feed pressure up to 1.0 bar results in an average temperature difference of 60.08 °C. In contrast to this the average temperature difference rises only slightly by about 13 °C in the case of a further feed pressure increase by about 0.5 bar from 1.0 bar to 1.5 bar.

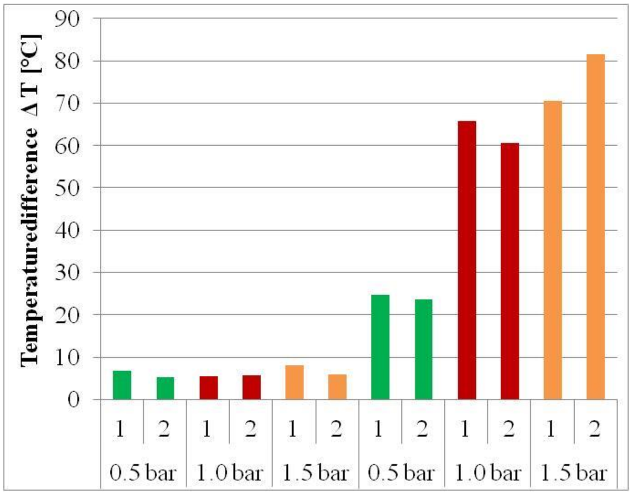


Fig. 7. Comparison of the temperature differences at 390 °C achieved by spraying with the dosage and conventional nozzles

To complete the analysis of the thermal effect of the minimal die lubrication the average volumes were measured for both nozzles, according to application parameters used for evaluating the temperature drops (see Table 1).
The results of the measurement of the output volumes at a spraying time of 0.5 s for both the conventional and the dosage nozzle are summarized in table 2. The differences of volumes put out by the conventional and the dosage nozzle differ in dependency of the feed pressure. So at 0.5 bar feed pressure the output volume of the conventional nozzle is about 60 times higher than the output of the dosage nozzle (0,58 g to 0.01 g). At a feed pressure of 1.0 bar and 1.5 bar both the output volume of the conventional nozzle is 40 times higher. Interpretation of this result is that under 1.0 bar the dosage nozzle is not completely load.

Table 2: Measured output volumes ot the tested nozzels

Feed pressure	Conventional nozzle	Dosage nozzle
0.5 bar	0.58 g	0.011 g
1.0 bar	0.80 g	0.019 g
1.5 bar	0.98 g	0.023 g

CASTING TRIALS

With a focus on the main research aspect, the possibility of increasing the weldability of die cast parts by using minimal die lubrication, casting trials were carried out. In these casting trials test parts were produced and then analyzed.
According to studies about the difference between conventional and minimal die lubrication, both systems were tested in casting trials.

These trials were conducted on the high-pressure die casting machine of the TU-BS (ifs), equipped with a fully automated die spraying system, which can be adapted to both spraying systems to be tested.
To meet the requirements of the research concerning the influence of release agents on the weldability of die-cast parts, a test die was developed at the institute of joining and welding.
This die has the geometry of a square sheet, height: 150 mm, width: 260 mm and 4 mm thickness.
Figure 9 shows the CAD model of the ejector side of the test die (Fig. 8 A) and the model of the cast part (Fig. 8.B). The die can be fitted with different venting devices (passive die venting or vacuum valve), so in Figure 9 no venting device is shown.

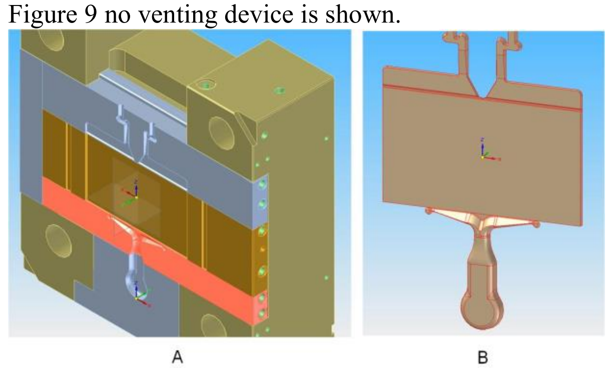


Fig. 8. CAD – Models of the test die (A) and cast part (B) for release agent test trials

The whole thickness of 4 mm is formed in the ejector die. This means the injector die is plain-shaped. The advantages of this design of the die are:

- Constant release conditions: the cast part always remains in the ejector die while opening
- Plain test piece surface
- Reduced workload for assembling, because another plate thickness can be achieved by setting up a new ejector die

Casting trials (Experimental Design)

The plain sheet geometry for the test pieces realized by the chosen die design provides a wide range of possibilities of analysis to be applied.
So specimens for mechanical tests according to different test standards can be manufactured easily. This can also be applied to the preparation of microsections and specimens for welding tests.
As regards the testing of surface formation, the sheet shape test design allows to conduct EPMA (Electron Probe Micro Analysis) measurements of defined surface areas.

As the estimated application area of weldable die cast parts are, for example, automobile structures demanding high ductile alloys, a primary alloy was chosen to cast the test parts. The accurate composition of the cast primary EN AC- AlSi10MnMg alloy is given in Table 3.

Table 3: Chemical analysis of the used AlSi10MnMg alloy (wt. %)

Si	Fe	Cu	Mn	Mg	Zn	Ti	SR
10.57	0.0082	0.001	0.54	0.276	0.008	0.061	0.014

In order to fulfill the aim of evaluating the minimal die lubrication based on the application of corresponding release agent concentrates in comparison to conventional die lubrication, both solutions were tested.
For lubricating the die in the conventional method, a wax-free, water-based release agent containing polysiloxane was selected. This selection was based on the experiences with deploying this release agent for casting weldable parts.
Keeping the output of organic substances as low as possible this release agent was applied at a dilution ratio of 1:125.
Corresponding to this an also wax-free release agent concentrate was selected for the minimal die lubrication. An overview the parameters relevant for testing the different die lubrication systems is given in Table 4. Based on each parameter set a batch of 50 plates was cast.

Table 4: Overview release agent tests

Release agent	Dilution ratio
wax-free, conventional	1:125
wax-free, minimal	concentrate

Analysis of the test pieces

To evaluate the suitability of the selected release agents for the production of weldable structural parts, two testing methods were applied; these were a re-melt test and Electron Probe Micro Analysis.

Re-melt test

The re-melt test provides a quick testing method, simple to apply, as standard equipment can be used. So for the generation of the re-melt seam, a conventional TIG (Tungsten Inert Gas) welding torch can be adapted. For the re-melt test the TIG welding torch was mounted on a linear running gear. This setup allows a movement of the TIG arc with constant velocity and arc length. Three parts were tested per batch. The relevant test parameters are the following:

- Arc-Current: 90 A
- Arc length: 3 mm
- Velocity (torch movement): 200 mm/min

To identify local differences of the weldability of the test parts, re-melt seams were generated near and opposite the ingate, as show in the draft given in Figure 9.

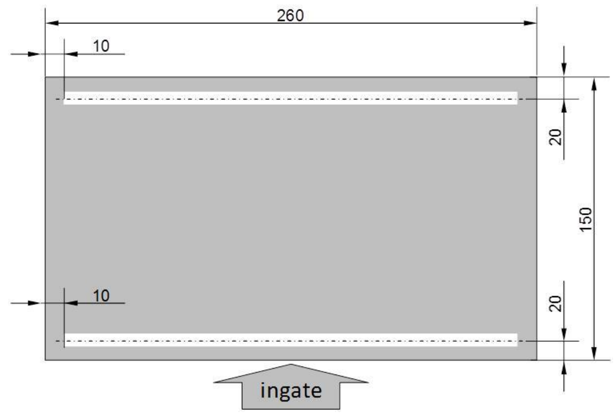


Fig. 9. Draft of test plate showing the position of the re-melt seams (white areas)

Criterion for evaluating the test results is the formation of the re-melt seam, especially the pollution and surface pore formation. So the visual inspection of weld seams and therefore the re-melt seam is common use. If the surface smoothness is deficient, as too many pores appear, it is evident that the internal pore formation is also too high.

Electron Probe Micro Analysis

The overlay of the component surface with thermally disintegrated release agent artifacts is an additional gas application source during welding and is difficult to analyze or to quantify in specific locations. So the TU-BS (ifs) developed a special method of analysis which is based on an EMPA area measurement of the local carbon distribution by means of ESMA (electron beam micro analysis). With this procedure the elements, from boron to uranium, can be identified with a high element-dependent detection limit (0.01 to 0.001 %) and with a local resolution in the µm range. With this procedure, the determined depth is 1 µm on average, but assuming that the carbon from the disintegrated release agent residues is only at the surface, the identification of layer thicknesses is possible in the nm range. Due to the numerous measuring points during the automated measurement, differentiated statements as regards the carbon layer are possible. In particular, a reliable statement as regards the release agent distribution in the area near and opposite the ingate is possible.
So in addition to the re-melt test the carbon layer thickness was measured by using electron probe micro

analysis (EPMA). Therefore specimens were cut out of the test plate. These specimens have a square geometry (20 mm wide; 10 mm high). The positions of the specimens (S1 to S5) are marked in the draft of the test plate given in Figure 10. As this test is time-intensive, only one plate of each batch was tested.

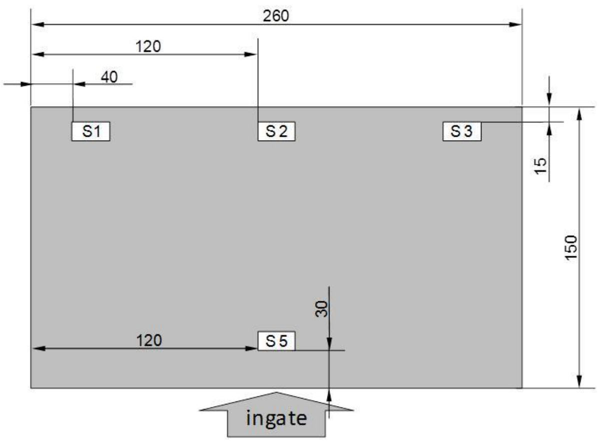


Fig. 10. Positions of the EPMA specimen on the test plates

Results of the Re-melt test

The optic analysis of the re-melt seams on the test plate surfaces showed only slightly pronounced deviations comparing the influence of conventional and minimal die lubrication.

Appling both types of lubrication results in minimal surface pore formation and pollution. Examples of the generated re-melt seams are shown in Figure 11, picture A of Figure 11 representing an overview of a test plate cast by applying conventional die lubrication and picture B of a test plate cast by using minimal die lubrication.

As regards local differences in the re-melt seam formation it is to note that a light increase of surface pollution opposite the ingate can be seen on the plates cast with conventional die lubrication.

Pictures showing examples of the re-melt seam in detail are mentioned below in Figure 12. In both cases the smooth and less polluted seam surface is visible. The formation of surface pores is at a very low level.

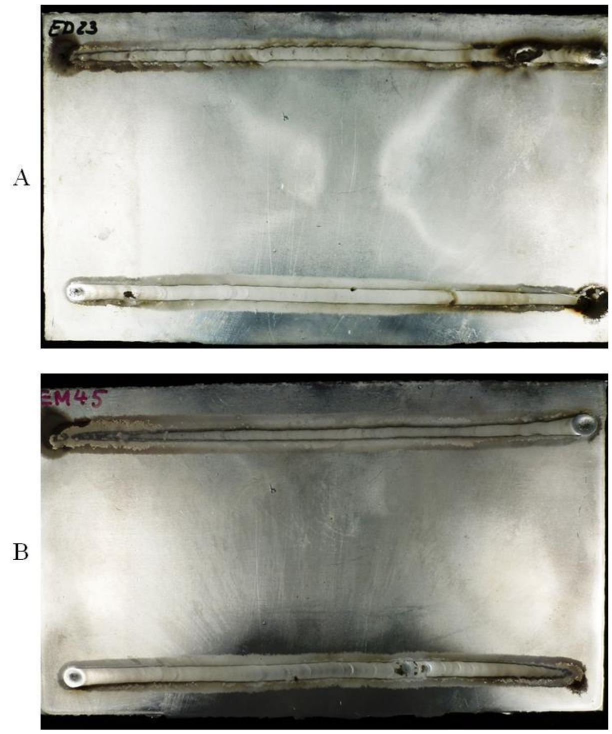


Fig. 11. Examples overview re-melt test seams; A) conventional; B) minimal die lubrication

Fig. 12. Details of the re-melt seam in the area opposite the ingate A) conventional; B) minimal die lubrication

In addition to the optical inspection of the re-melt seams the internal pore formation was investigated by computer tomography.

The pore analysis of the re-melt seams stated the low pore formation in plates cast with conventional and minimal die lubrication. Whereas the use of the minimal die lubrication provides a significant less pore formation. It is to mention, that the minimal die lubrication was used in combination with a vacuum assisted die venting. But as investigated in former studies [2], the die venting has a minimal effect to the gas content of die cast parts, responsible for the weldability.

Examples of the pore analysis are shown in Figure 13. Whereas picture 13.A shows the analysis of a plate cast with conventional die lubrication and picture 13.B of a plate cast with minimal die lubrication. The shown examples of the analysis correspond to the areas of plates presented in Figure 12.A and 12.B.

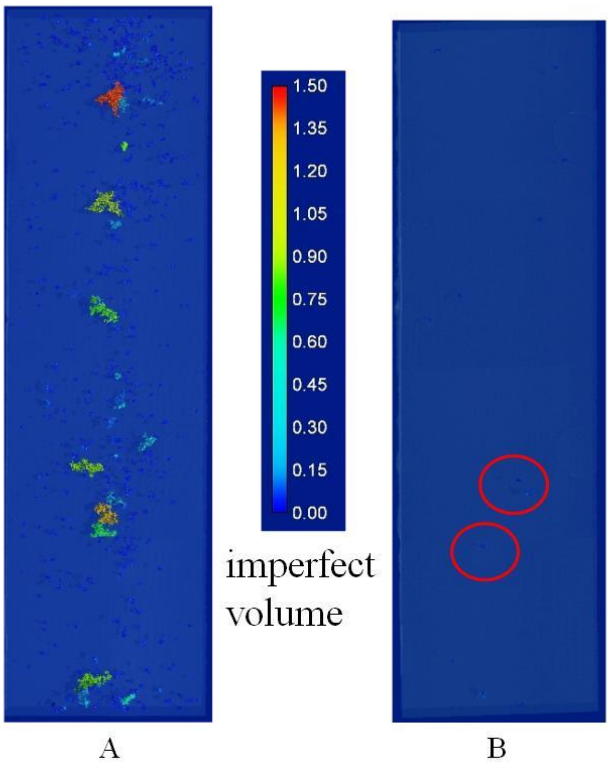


Fig. 13. Examples of the pore analysis of the re-melt seam in the area opposite the ingate A) conventional; B) minimal die lubrication

Results of the EPMA

In accordance with the re-melt tests, the EPMA results were applied to specimens from each parameter set mentioned above (see Table 3).
The specimen for the EPMA was cut out of the test plates according to the sketch given in Figure 10. The area of analysis has the following specification:

- 100 x 100 points
- 10 µm point-to-point distance
- 1 x 1 mm measurement area

With respect to the results of the re-melt test, a slight local difference in the release agent residual disposition can be identified. So the carbon layer thickness, used as an indicator for release agent residuals, is a little higher in the area opposite the ingate than in the area near the ingate. This applies to the specimen cast with conventional die lubrication as well as the one cast with minimal die lubrication. Examples of the measurement results are presented in Figure 14 and Figure 15. The graphic given in Figure 14.A shows the spread of carbon layer thickness opposite the ingate on the test plate cast with conventional die lubrication (position S3 Figure 10). Average value of this measurement is 14 nm.
The carbon layer thickness measured on the same plate near the ingate (position S5, Figure 10) is graphically shown in Figure 14. B. Average value of this measurement is 14 nm.

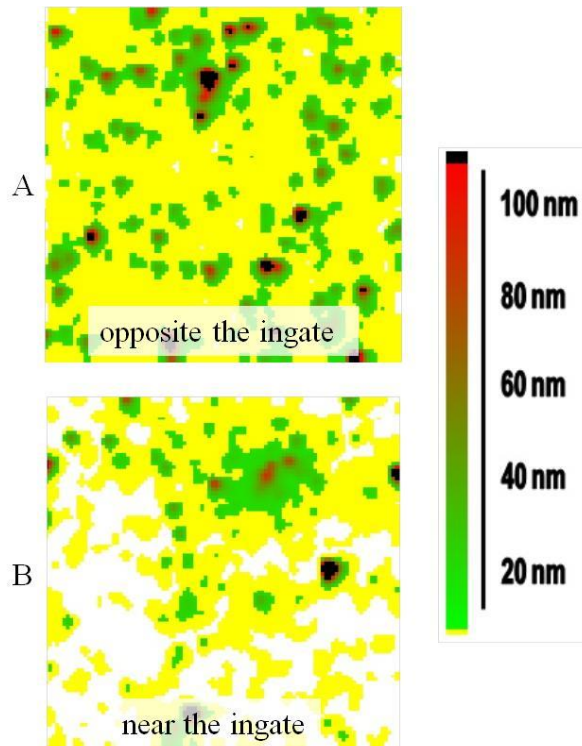


Fig. 14. Carbon layer thickness (EPMA) measured on a test plate cast with conventional die lubrication

In the case of the analyzed specimen being taken from the plates cast with minimal die lubrication an increase of the carbon layer thickness occurs. So the average carbon layer thickness opposite the ingate is 20 nm and 16 nm near the ingate. Corresponding graphics of the measurement are given in Figure 15, Figure 15.A representing the measurement opposite the ingate and Figure 15. B the measurement near the ingate.

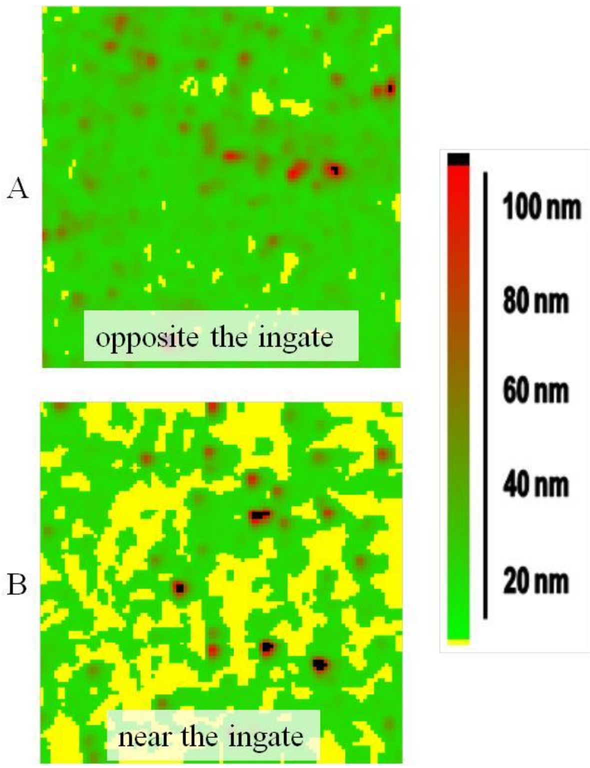


Fig. 15. Carbon layer thickness (EPMA) measured on a test plate cast with minimal die lubrication

CONCLUSION

In the first part of the studies concerning the minimal die lubrication respectively the micro spraying, the possibility of minimizing the thermal shock induced by release agent application was investigated on a test stand. Comparative measurements of the temperature drops generated by the release agent application confirmed the estimated low effect of the micro spraying technique.
Key element of the tested system is a dosage nozzle, limiting the amount of applied release agent. Compared to a conventional continuous working nozzle, significant differences in the temperature drops occur. These results confirm the capability of decreasing the thermal stress of the die. A restrictive condition for applying the test micro spraying system is a well functioning internal die cooling. So the measurements of the temperature drops starting at high temperatures also state that minimal die lubrication is not usable for cooling hot spots in the die.
The casting trials carried out in the second phase of the research confirmed the function of the minimal die lubrication in the experimental foundry.
It shall be mentioned that the use of the minimal die lubrication requires an adjustment of the spraying parameters to avoid an over-spraying, which means too much release agent can be applied resulting in inadequate part properties.

As far as the weldability of die cast parts is concerned, the analysis of the cast parts confirmed the possibility of producing weldable die cast parts by applying the minimal die lubrication.

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REFERENCES

1. Pries, H., M. Rethmeier, S. Wiesner, H. Wohlfahrt: Laser- und Elektronenstrahlschweißen von Aluminium-Druckguss. DVS-Berichte Band 220. Verlag für Schweißen und verwandte Verfahren DVS-Verlag GmbH, Düsseldorf 2002, S. 219-224
2. Wohlfahrt, H., J. Ruge, N. Grov, D.-H. Rehbein: Schweißen von Druckguß - Verfahren und Metallurgie Jahrbuch der Schweißtechnik 1996, DVS-Verlag Düsseldorf, 1996, S. 39/46
3. Börner, C., S. Böhm, K.Dilger: Elektronenstrahlschweißen von duktilen Aluminium-Druckguss-legierungen. XXX. Assistentenseminar Fügetechnik und Schweißtechnik, Burg Warberg 03.-05.09.2009, DVS-Berichte Band 268 (2010), DVS Media GmbH, Düsseldorf , S. 59-63, 2010.
4. Pries, H., S. Liluashvili, K. Dilger: Brandrissentstehung an Druckgießformen. Druckguss-Praxis (2003), H. 3, Schiele & Schön GmbH, Berlin, S. 135-140
5. Herrman, C., Pries, H., Hartmann, G. “Energie- und ressourceneffiziente Produktion von Aluminiumdruckguss, Ergebnisse des Verbundforschungsprojektes ProGRess, Springer Verlag 2013