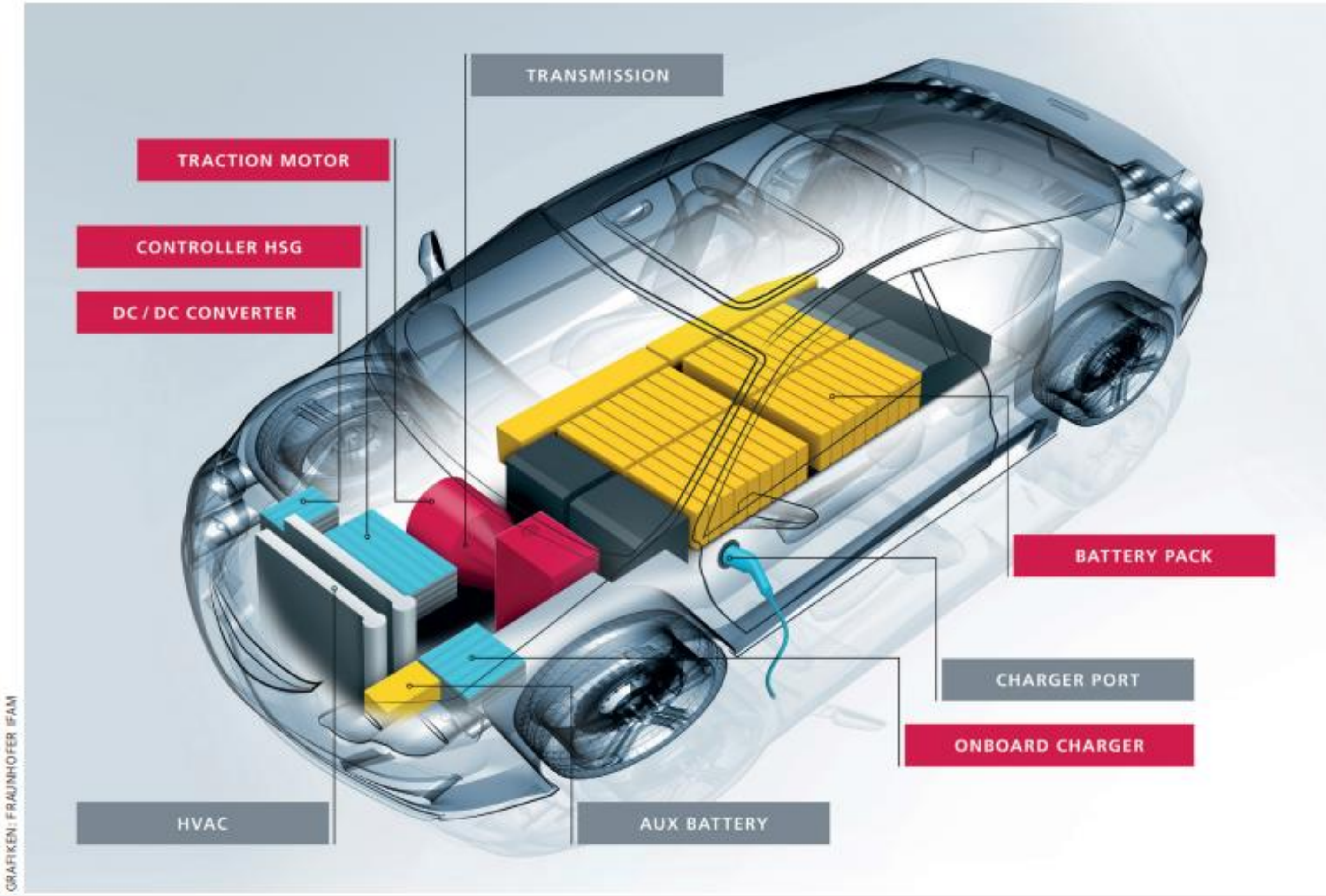

Electric powertrain components that require temperature control. The components with a red background are particularly suitable for direct cooling.

Innovations for electro mobility

Leakage-free cooling channels for Die-cast housing components

The increasing advancement of electro mobility presents designers with new challenges when designing the components of the drive train. In addition to the maximum power density the focus is now on the optimization of the thermal conditions. Geometrically complex channel structures for guiding the cooling medium must already be integrated into housings for batteries or power electronics as well as the motor itself in the manufacturing process. This requires new manufacturing concepts, which combine performance and economic efficiency and are supported by valid simulation approaches.

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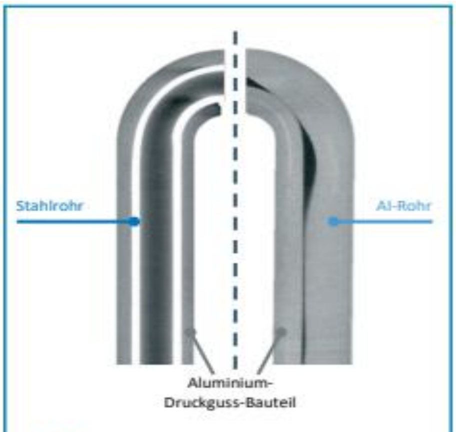
With wide market launch of electro mobility, less relevant phenomena come into focus when designing components of the drive train. Whilst the power density was in the focus of the developer so far, which could be used for performance increase or lightweight construction, today more than ever, compliance of the optimal thermal conditions is in the foreground. If we look at the setup of an electrically powered vehicle



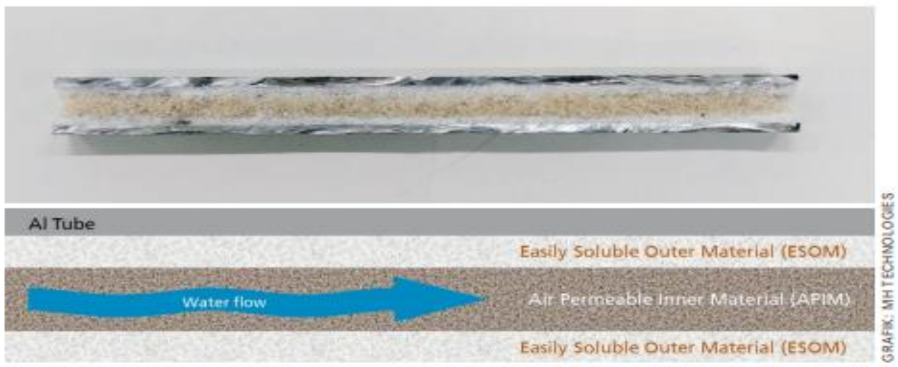


Image 1: Pipes cast in for cooling engine components. The Steel pipe (left) withstands the manufacturing process; the aluminum tube (right) collapsed.

Image 2: ZLeak Tube Technology: The two-component structure with a porous inner cross-section makes it much easier to remove the filler: a) Filled tube in cross section, b) a schematic representation of the principle of filler removal.

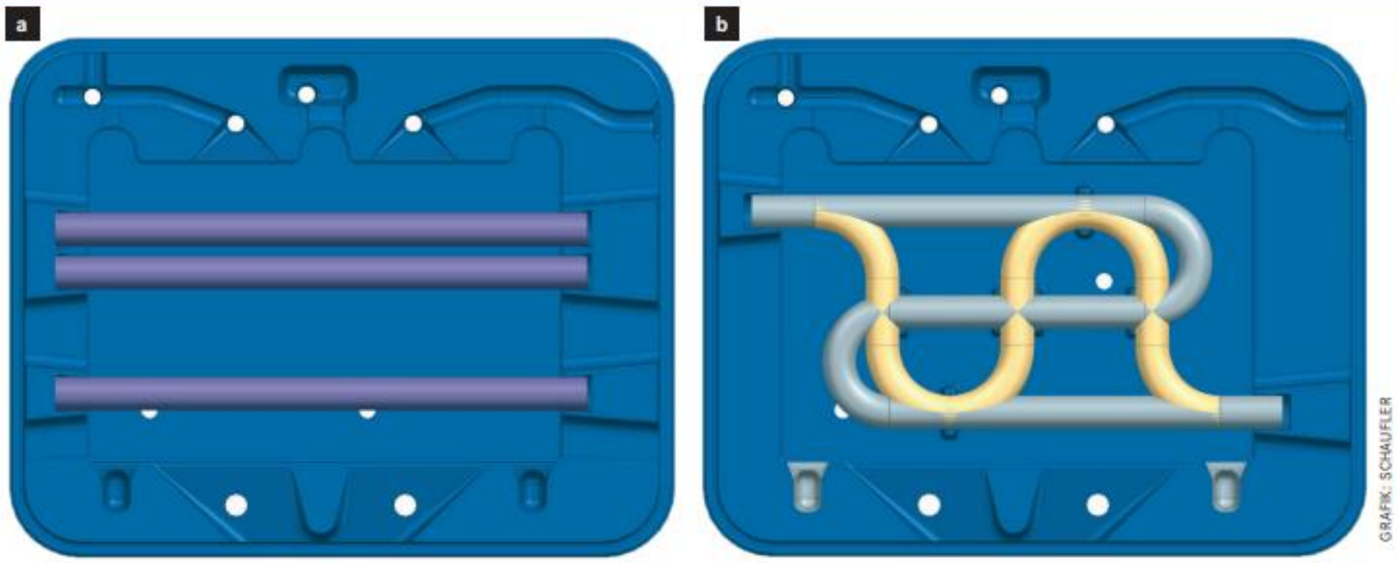


Image 3: Mold inserts to determine the influence of different process parameters on stability, compression and deformation of ZLeak Tube pipes in the die casting process (developed and manufactured by Schaufler Tooling).

battery elements with their weight are coming to focus for lightweight construction primarily. Its rapid discharge will result in a temperature increase if no suitable countermeasures are taken, which in the end means power losses of the battery, going hand in hand with capacity losses. This is just one example showing to which extend the thermal aspects in context of electromobility are a key point to the design. In an electrically powered vehicle this subject concerns a large number of assemblies (see initial image). So, it arises the question of how the heat dissipation is controlled and an optimal temperature can be assured. Often die-cast components are from importance in which the channel structures for fluid-based tempering are integrated have to. This applies to the battery housing as well as the housings for power electronics or the traction motor itself. While the battery housings can at least have sections of straight channel structures, an electric motor requires geometrically more complex hollow structures.

Cooling concepts for traction motors

Depending on the production process this led to different technological approaches for the realization of the media leading channels in electric motor housings in the market. If the housing in not made in high pressure casting, but in low pressure or Gravity casting, sand cores have proven to be most efficient [1, 2].

Limiting factor is the lower productivity of the concerned casting processes. An alternative, which can also be easily implemented in high pressure die casting, is the two-piece setup of the housing.

However, this approach is expensive due to the necessity of an additional mold, the additional processing effort and the joining processes. Depending on the embodiment weld connections are required or there must the joining and sealing surfaces have to be machined. In operation there is a special challenge from the temperature difference between inner and outer housing resulting in thermal

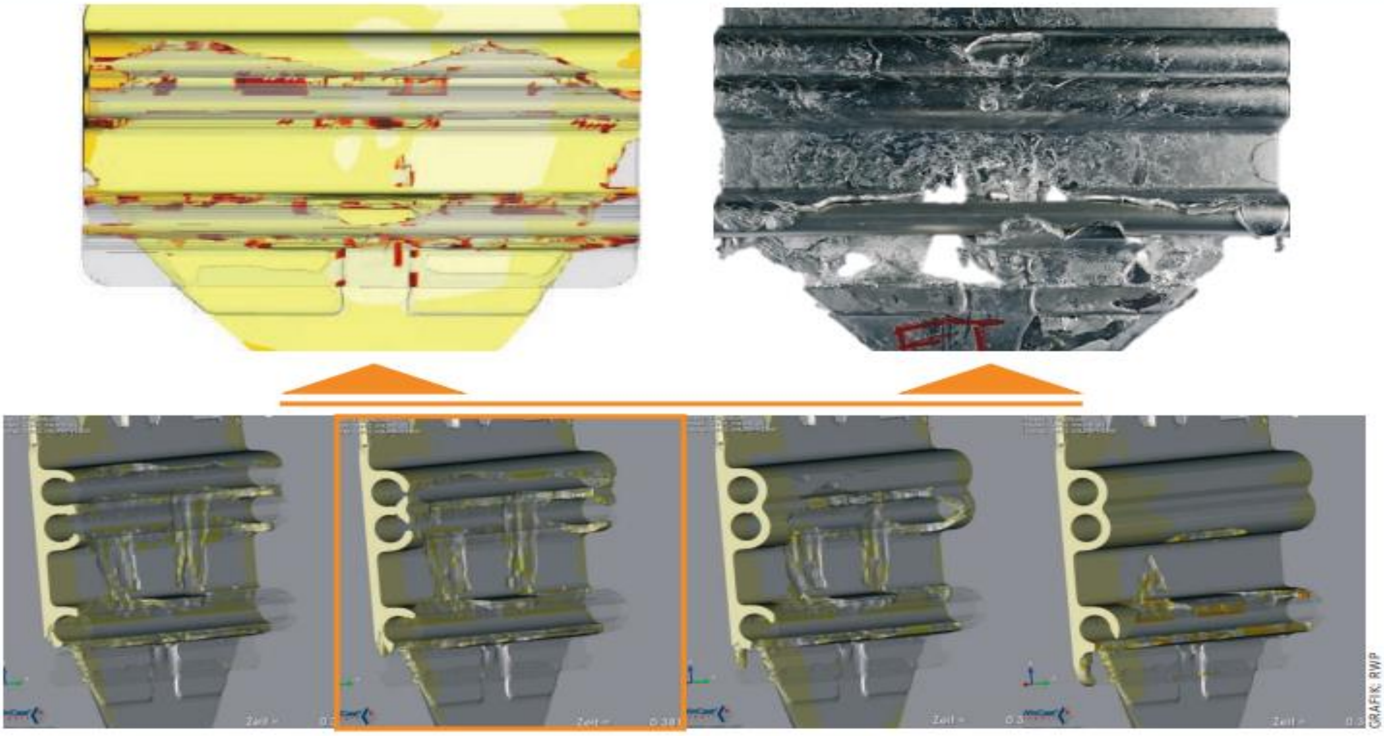


Bild 4: Validierung der seitens der RWP GmbH mittels WinCast expert durchgeführten Simulation. Der Abgleich erfolgte über Gießversuche mit unterbrochenem Schuss.

Image 4: Validation of the simulation carried out by RWP GmbH using WinCast expert. The comparison was carried out using pouring tests with an interrupted shot.

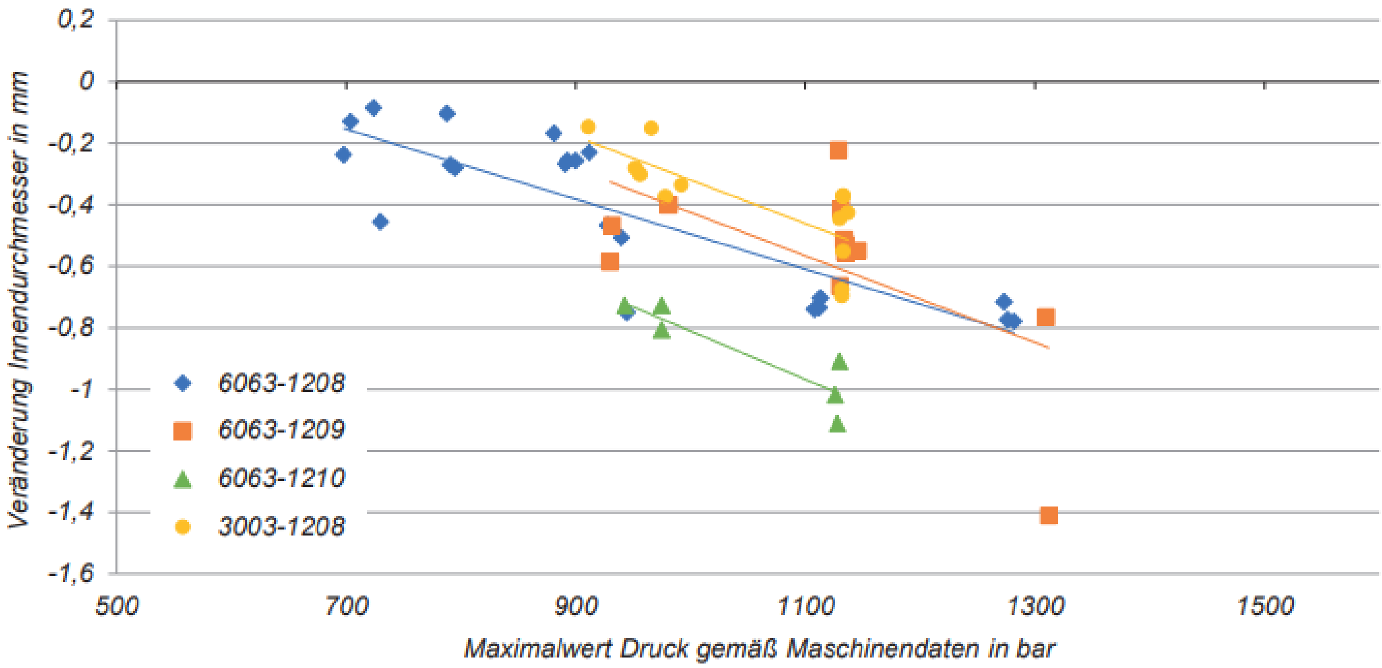


Bild 5: Abhängigkeit der Kompression unterschiedlicher Rohrvarianten vom Gießdruck.

Image. 5: Dependency of the compression of different pipe variants on the casting pressure.

tensions that have to be absorbed by the joining and sealing concept. A one-piece housing can be made possible if the cooling channels are prefabricated as an insert in the casting tool and casted around. Examples of this type exist in the form of hydraulic lines in Gearboxes like the 8HP model of ZF Friedrichshafen AG [3, 4], but in this case steel pipes are used which due to the higher stability can withstand at casting temperature in the high pressure die casting. This solution is usually acceptable for hydraulic systems, for component temperature control however, alternatives based on Aluminum tubes or hollow profiles are preferred. The reasons for this are only partially of thermal nature and can be summarized as follows:

> higher thermal conductivity of aluminum compared to steel,

> better adaptation of the thermal expansion coefficient to the casting,

> reduced gap formation between cast part and insert,

> Avoidance of the risk of contact corrosion between the cast part and the insert.

In practice, however, it has been shown that directly casting unreinforced aluminum hollow profiles are not stable in the die- casting process. Image 1 illustrates this using a steel and aluminum tube cast in the same tool under the same process boundary conditions.

ZeroLeak Tube Technology

The use of the advantages of one-piece housing requires a corresponding solution to stabilize the cast pipes. The classic approach is the use of a filler, which after pouring can be removed. An example is the Combicore approach based on a mechanically compacted salt filling [5]. An alternative procedure was developed and patented by the Korean company MH Technologies [6, 7]. Merchandised under the name ZLeak Tube it is also based on a filler to be removed after pouring, which, however, has a two-layer structure (Image 2). The philosophy behind it is that the outer layer is made from a water-soluble material whereas the inside is a coarse-grained particulate and thus media-permeable material which stabilizes the outer layer. This enables the pipes to be bent without damaging their inner walls inadmissibly and without buildup of the filling material on the inner wall of the pipe are avoided. At the same time the media-permeable core allows it to easily rinse out the filling which the reduced volume fraction of the salt is further favoring. As a result, the ZLeak Tube technology allows the production of complex shaped cooling channels with round, but also elliptical or rectangular cross-sections. Also the processing of multi-chamber hollow profiles is possible based on this method.

Influence of process parameters on the casting result

The fundamental suitability of ZLeak Tube pipes for use in pressure casting has already been proven, not investigated however, were among others:

> the process limits within which hollow structures of this type can be processed,

> the effect of various process parameters on compression and deformation of the pipes,

> the representability of these effects in the casting simulation and

> The evaluation of the application-related properties of such cooling channels.

The Project "CoolCast - New Approaches for High Efficiency Cooling of Electric Drives " is dedicated to these questions. Besides MH Technologies as developer of the ZLeak Tube technology, the companies ae group ag (die casting), Schaufler Tooling GmbH (tool making) and RWP GmbH (simulation) in cooperation with Fraunhofer IFAM address the aforementioned challenges. The project is divided into several phases in which on the basis of test components with increasing complexity (Image 3) correlations were determined in order to gain knowledge and transfer it to an electric motor housing demonstrator component. The required die casting tools were provided by AE Group AG, the development of mold inserts and the modification of the existing tools were under the responsibility of the company. Schaufler Tooling GmbH, whose tasks also include the development of concepts to fix the pipes in the mold. The initial sampling of the adapted tools including the determination of suitable parameter sets for the casting process took place again at the ae group ag. At the same time, MH Technologies optimized the filling and shaping technology in with focus on minimizing the achievable bending radii.

The focus of the investigations lay on pipes made of EN AW-6063 with an outer diameter of 12mm and wall thickness of 2 mm (6063-1208). In addition, there were variants with 1.5 mm (6063-1209) and 1 mm wall thickness (6063-1210) as well as those with 2 mm wall thickness from EN AW-3003 (3003-1208) considered. The quantitative relationships presented below are based on trials with the insert for holding straight pipes (see Fig.3a) and were confirmed through further experiments with curved pipes (see Fig. 3b). The relevant parameter studies focus on the first mentioned material variant 6063-1208 and on pipes in the gate nearest position according to Figure 3a. The temperature of the casting chamber and mold was kept constant at 220°C. The alloy used for casting was AlSi10MnMg at a temperature of 730°C. The corresponding casting tests were carried out following the sampling at the ae group ag on a Bühler-SC/N-66 die casting machine at the Fraunhofer IFAM in Bremen.

The following process parameters were varied (standard parameter set in bold):

> Casting pressure: 600 - **800** – 1000 - 1200 bar,

> Speed of casting piston: **2.5** - 3.5 - 4.5 m / s,

> Pipe temperature when inserting:

RT - 100-200 ° C.

In advance the mold filling and solidification was simulated by the company RWP GmbH using the simulation software WinCast-expert. An experimental comparison was made based on casting tests with interrupted shot, which could proof the correct image of the progression of the mold filling (Image 4).

The order in which individual areas of the cavity are filled, the front of the melt under the pipes, the reflection on the mold wall opposite the gate and the enclosing of the pipes only after this process can be found both in the Simulation as well as in the filling tests. With this, results of the simulation can be used to evaluate any intermediate stages of the filling process and their influences on the inserts. In particular, this does apply to positions which are difficult to access via physical measuring points on which virtual sensors can be used (see section Simulation). This comparison also forms the basis for using the simulation tool for design of the demonstrator components and the associated tools.

Compression and relocation of the Tubes

Experiment

In the following the experimental results on the dependence of the compression and displacement of the pipes on central process parameters and boundary conditions are shown. The pipe which was located closest to the gate was considered, since, as expected, the most dominant effects occurred here. X-rays form the basis of the evaluation of the castings. The specified values of the displacement are therefore considered to be projections of the actual shift to the mold parting line.

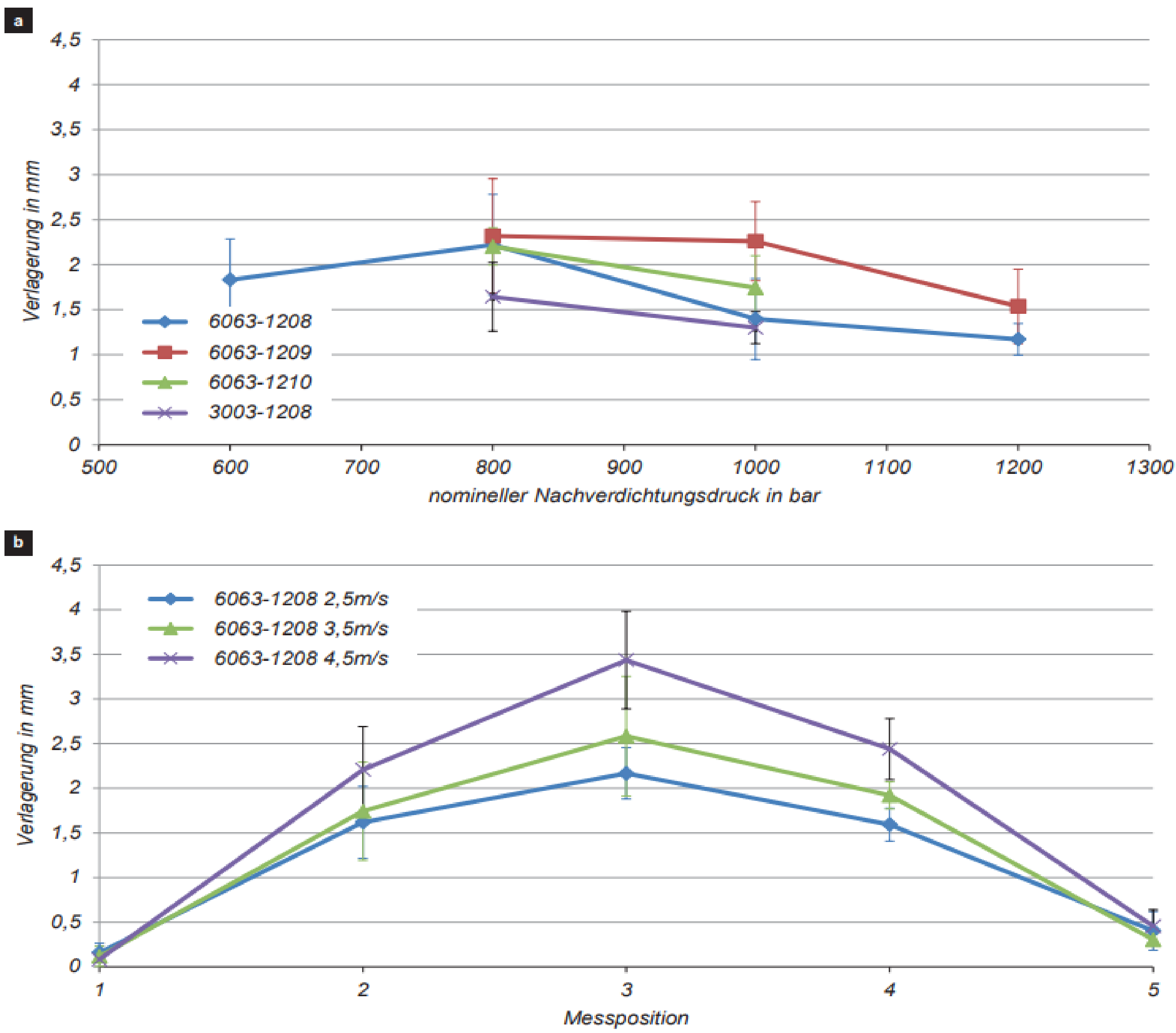


Bild 6: Abhängigkeit der Verlagerung unterschiedlicher Rohrvarianten von den Parametern bzw. Randbedingungen:

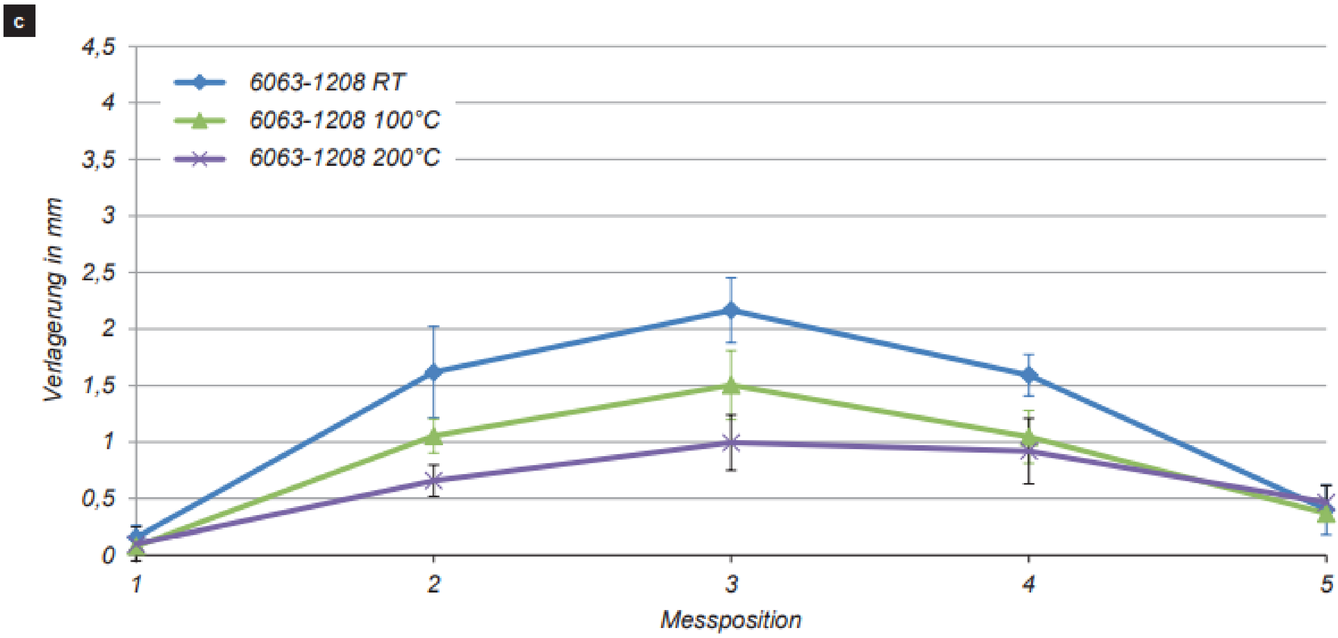
Image 6: Dependence of the displacement of different pipe variants on the parameters or boundary conditions:

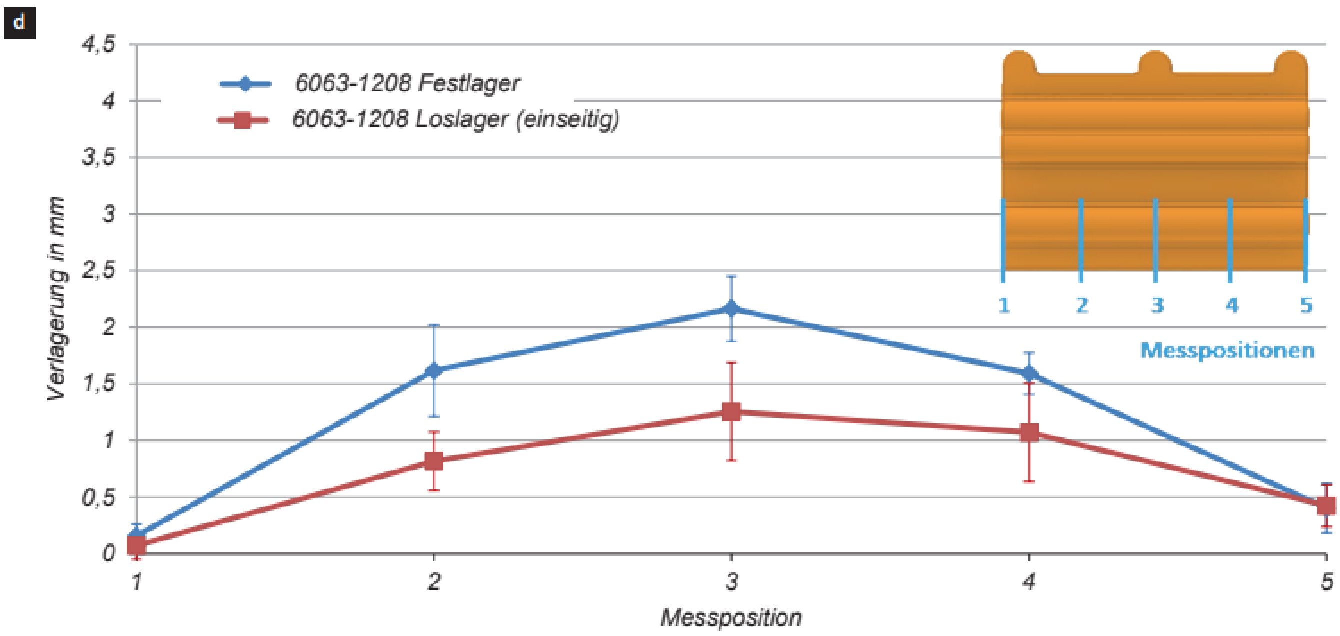
Image 5 shows the dependency of the compression of the pipes from the pressure level for different material and geometry variants. As a measure of the compression the reduction of the inside diameter of the tubes was chosen. The measuring location is the middle of the tube. The underlying pressure values are not about the nominal recompression pressure, but about the maximum pressure measured on the casting piston.

The summary of the results shows an approximately linear dependence of the compression on the pressure level. The influence of the wall thickness is not clear. If you take the relatively large spread of the data for this configuration, it shows that the tubes of the Alloy EN AW-6063 with 1.5mm Wall thickness behave similarly to those with a wall thickness of 2 mm. In contrast, pipes made of the same material show with a wall thickness of 1 mm, a significantly more pronounced reduction in diameter. This could be due to the fact that this Variant has a higher proportion of porous filler and thus tends to be more compressible. In this case it would be expected that with a further increase in pressure, which however is hardly technically relevant, the curve would be saturated. Pipes with a wall thickness of 2 mm made from EN AW 3003, on the other hand, are characterized by a lower level of compression than similar tubes made from EN AW-6063.

In contrast to compression, primarily determined by the pressure level, the relocation of the pipes is influenced by several parameters (Image 6). In Fig. 6a) the displacement was determined in the middle of the pipe, while in Figure 6b) - d) 5 positions along the length of the pipe were measured. All measurements with the exception of those explicitly marked differently in Figure 6 d), samples were used with fixed bearings on both sides.

The diagrams show the already mentioned minor effect of the recompression pressure. They also show that the speed of the cross





a) Nachverdichtungsdruck, b) Gießkolbengeschwindigkeit, c) Vorwärmtemperatur der Rohre, d) Art der Lagerung.

a) recompression pressure, b) plunger speed, c) preheating temperature of the pipes, d) type of bearing

melt flow directed towards the pipe contributes massively to the relocation of the pipes. On the other hand, a preheating the pipes significantly reduce the effect, as well as a unilateral movable bearing. In summary, these results indicate that it is in particular thermal influences in conjunction with the existing degrees of freedom that are responsible for the deformation of the pipes. This wins the Inclusion of the casting simulation and the It enables mapping of the thermal conditions in the pipe during the casting process in importance for reliable design of the cast part and the determination of the optimal casting parameters

Simulation

The casting simulation allows an exact illustration of the temperature of the inserted pipes over time (Image 7). This requires the correct definition of the heat transfer coefficient, especially between the melt and the pipe. Alongside the thermal effect of the filling (heat conduction, heat capacity, heat transfer coefficient) should not be neglected. If those prerequisites are met, the temperature profile can be monitored using virtual sensors as shown in Figure 7. In this dedicated case under standard conditions (no preheating of the inlay, mold temperature 220 ° C, melt temperature 730 ° C, Recompression pressure 800 bar, casting piston speed 2.5 m/s, pipe variant 6063-1208) peak temperatures in the tube reach approx. 530°C. At these temperatures, the remaining yield point of the considered alloy EN AW 6063 lies at 10MPa independent of the original heat treatment, as well shown in the comparison with determined values via JmatPro. This is confirmed by experimental results, according to which unfilled aluminum pipes collapse or are infiltrated even at casting pressures below 400 bar. Based on these results, another attribute is the deformation

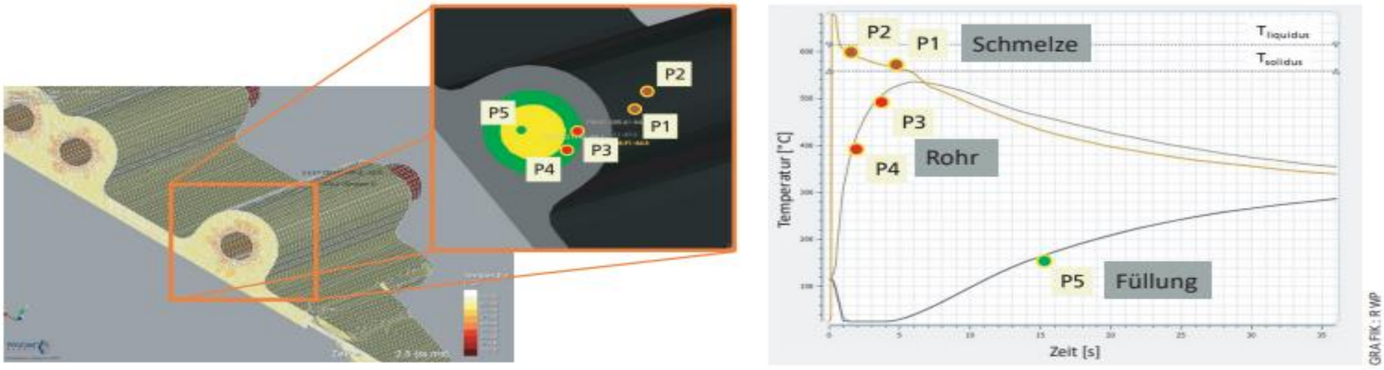


Bild 7: Die Simulation erlaubt die Ermittlung von Temperatur-Zeit-Kurven für jede beliebige Position sowohl im Gussteil als auch im Einleger. Im konkreten Fall ergeben sich im Bereich des Rohres im Verlauf von Formfüllung und Erstarrung Temperaturen von bis zu 530 °C, mit entsprechendem Festigkeitsverlust.

Image. 7: The simulation allows the determination of temperature-time curves for any position both in the cast part and in the depositors. In this specific case, temperatures of up to 530°C occur in the area of the pipe during the course of the mold filling and solidification, with a corresponding loss of strength.

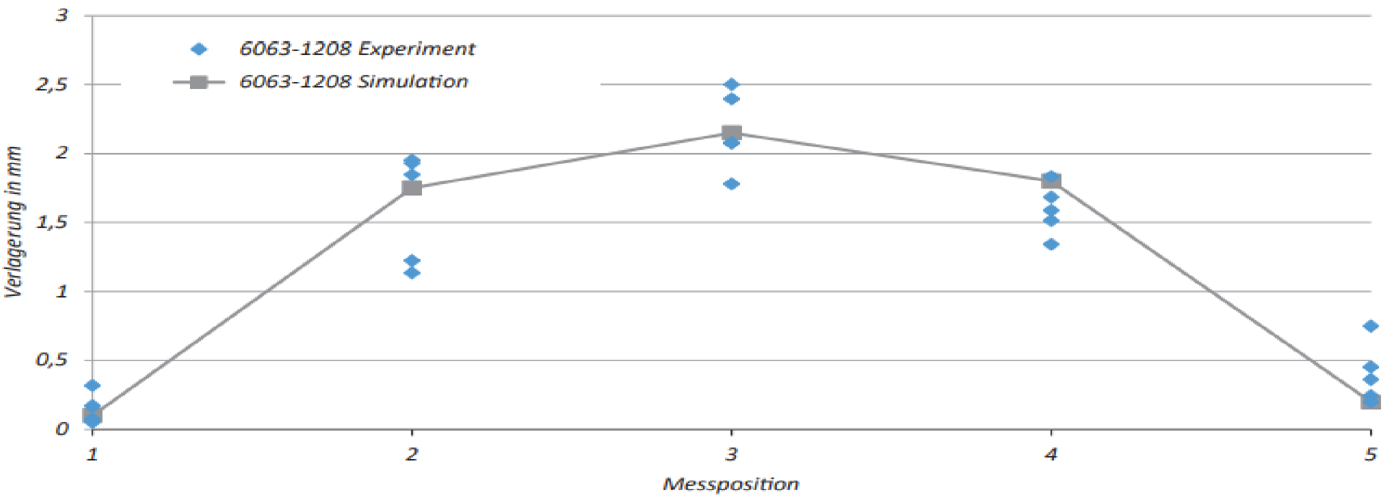


Bild 8: Vergleich zwischen über Gießsimulation prognostizierter und gemessener Verlagerung des Rohres nächst dem Anschnitt unter Standardbedingungen, d. h. Rohrwerkstoff EN AW-6063, Wandstärke 2 mm (6063-1208), Gießdruck nominell 800 bar, Gießkolbengeschwindigkeit 2,5 m/s, Temperatur von Form und Schmelze 220 °C respektive 730 °C, keine Vorwärmung der Rohre, beidseitiges Festlager.

Image. 8: Comparison between the predicted and measured displacement of the pipe next to the gate under standard conditions, which is predicted by the casting simulation, meaning Pipe material EN AW-6063, wall thickness 2 mm (6063-1208), casting pressure nominal 800 bar, casting piston speed 2.5 m / s, temperature of mold and melt 220 ° C respectively 730 ° C, no preheating of the pipes, both side fixed bearing.

of the cast pipes which can be determined using the casting simulation. From the form filling, solidification and cooling conditions as well as the storage of the pipes the occurring, primarily thermally induced forces, can be derived. The applied stress and deformation calculations show a distortion of a few tenths of a millimeter. The distorted geometries from the WinCast expert simulation software were exported as an STL file for the geometric evaluation and measured. Using this data the values of displacement as well as compression over the entire pipe can be determined. The correlation with the experimental results also show that the chosen approach not only applies to receive qualitative, but also for quantitative statements (Image. 8).

Heat transfer between Pipe and casting

To determine the heat transfer coefficient between the pipe outer wall and casting a testing setup was implemented at the Fraunhofer IFAM (Image. 9). For the assessment of the samples an area of about 49mm width was cut out around the single pipe from the casting (see Image. 9a). Through the leveled backside of the test specimen a Heating mat (heating power 154 W) is heating up the sample. Through the cast in pipe a defined volume flow of approx. 0.5 l / min of water is guided, whose temperature both directly before entering as well as immediately after leaving the cast part is captured. The evaluation of the measurement takes place after a steady state is set. During the measurement, the structure is thermally insulated against the environment. The registered temperature differences reach up to 5 ° C, depending on the variant tested. The entire system is described through a thermal substitute model that allows to define a heat transfer coefficient based on the measurement results for said heat transfer between pipe and casting.

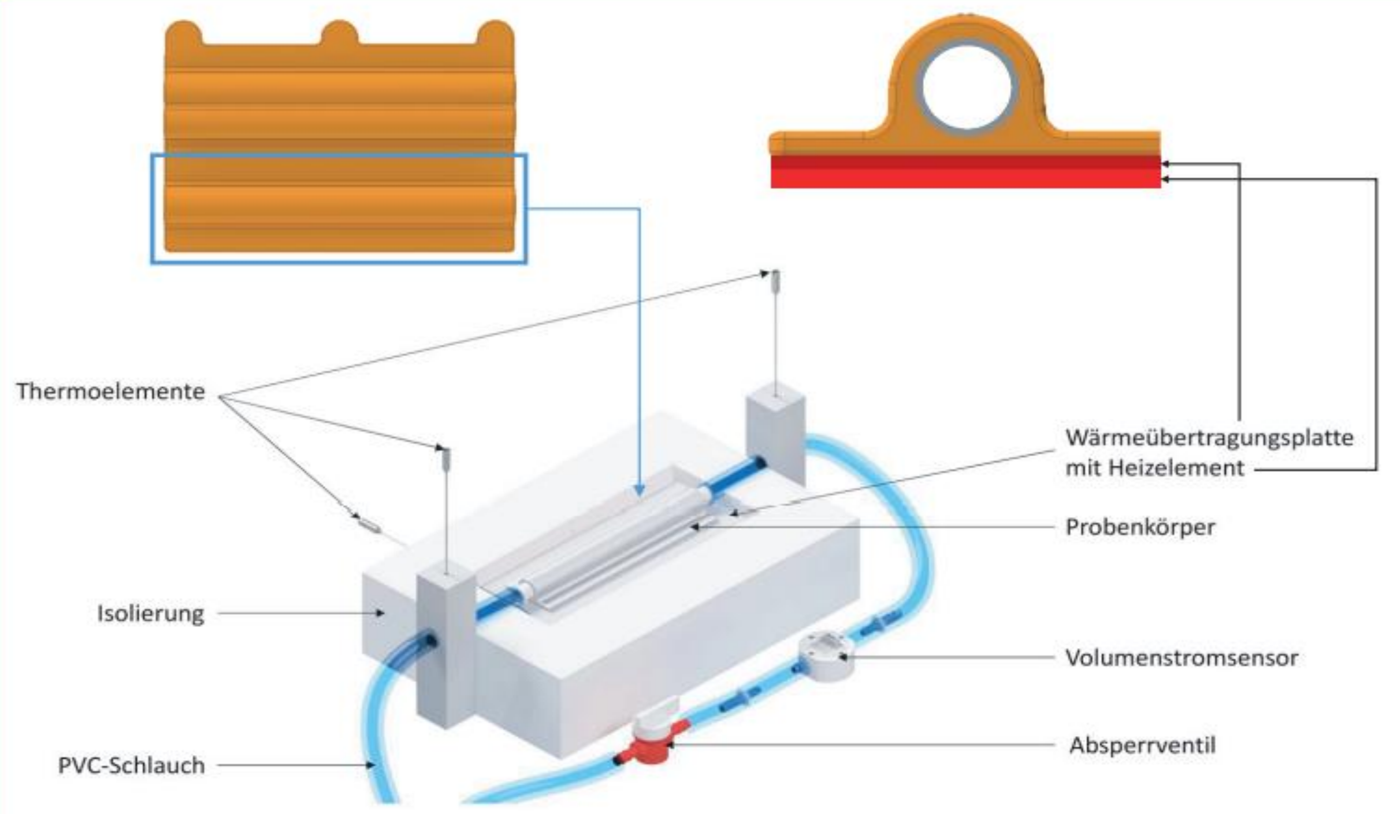


Bild 9: Funktionsprinzip des Versuchsstandes zur Bestimmung des Wärmeübergangskoeffizienten zwischen Rohr und Gussteil. Die eingebettete Skizze veranschaulicht, welcher Ausschnitt des Gussteils für die Messungen genutzt wurde.

Image. 9: Functional principle of the test setup for determining the heat transfer coefficient between pipe and casting. The embedded sketch illustrates which section of the casting was used for the measurements.

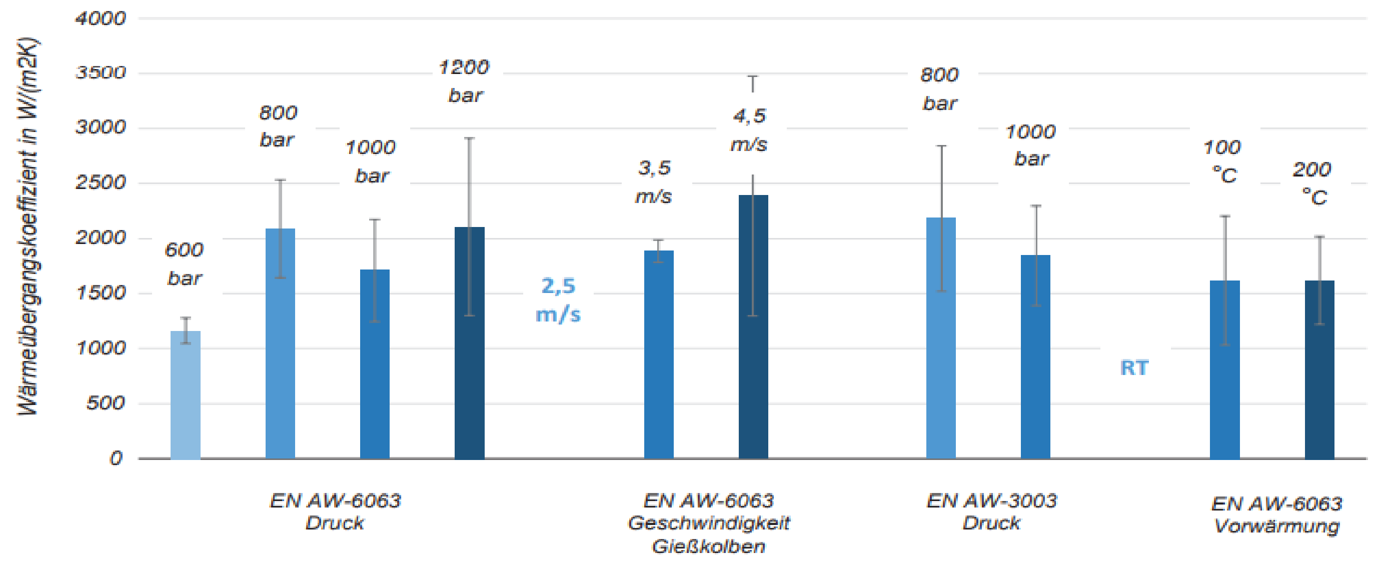


Bild 10: Messergebnisse zur Abhängigkeit des Wärmeübergangskoeffizienten von Nachverdichtungsdruck, Gießkolbengeschwindigkeit und Vorwärmung für die Materialvariante EN AW-6063 sowie vom Nachverdichtungsdruck für EN AW-3003.

Image. 10: Measurement results for the dependence of the heat transfer coefficient on the compression pressure, casting piston speed and preheating for the material variant EN AW-6063 and on the compression pressure for EN AW-3003.

The measuring system was evaluated in terms of reproducibility of the results successfully. One validation was carried out using a reference component machined from an AlSi10Mn-Mg-block (gravity casting process) matching the geometry of the cast part cutout. The available results show a tendency to improve the EN AW 6063 Heat transfer coefficients with increasing recompression pressure. This effect is not verifiable for EN AW-3003. In general, the measured values for the EN AW-3003 are higher than for EN AW-6063.

As expected, the Heat transfer coefficients underrun the value which was defined for the validation using the reference sample (Image. 10) but from an application perspective they reach a required measure.

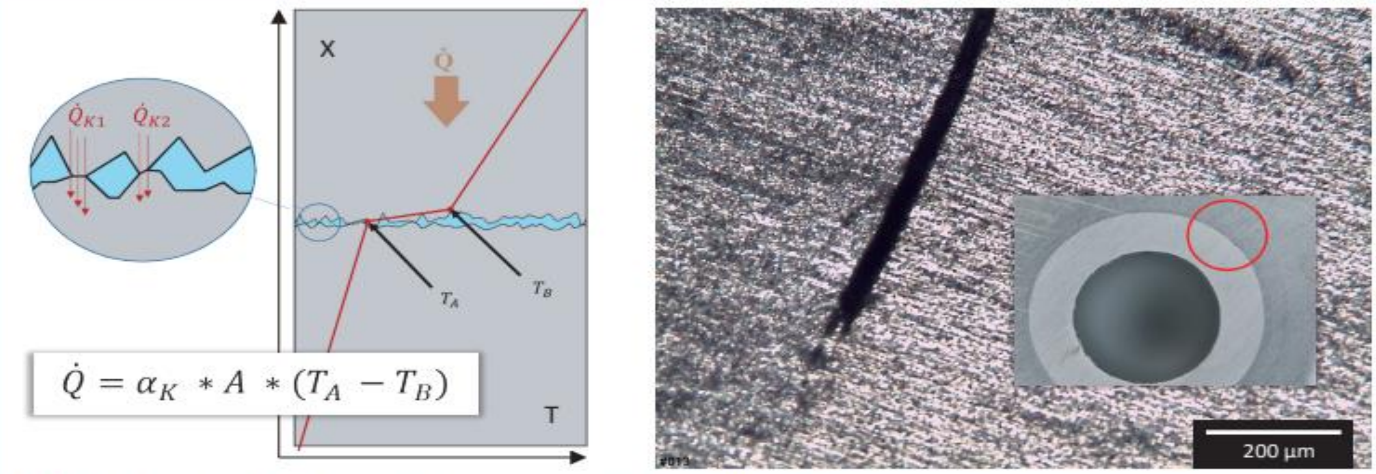


Bild 11: Problem der Spaltbildung und Einfluss derselben auf den effektiven Wärmeübergangskoeffizienten.

Image. 11: Problem of gap formation and its influence on the effective heat transfer coefficient.

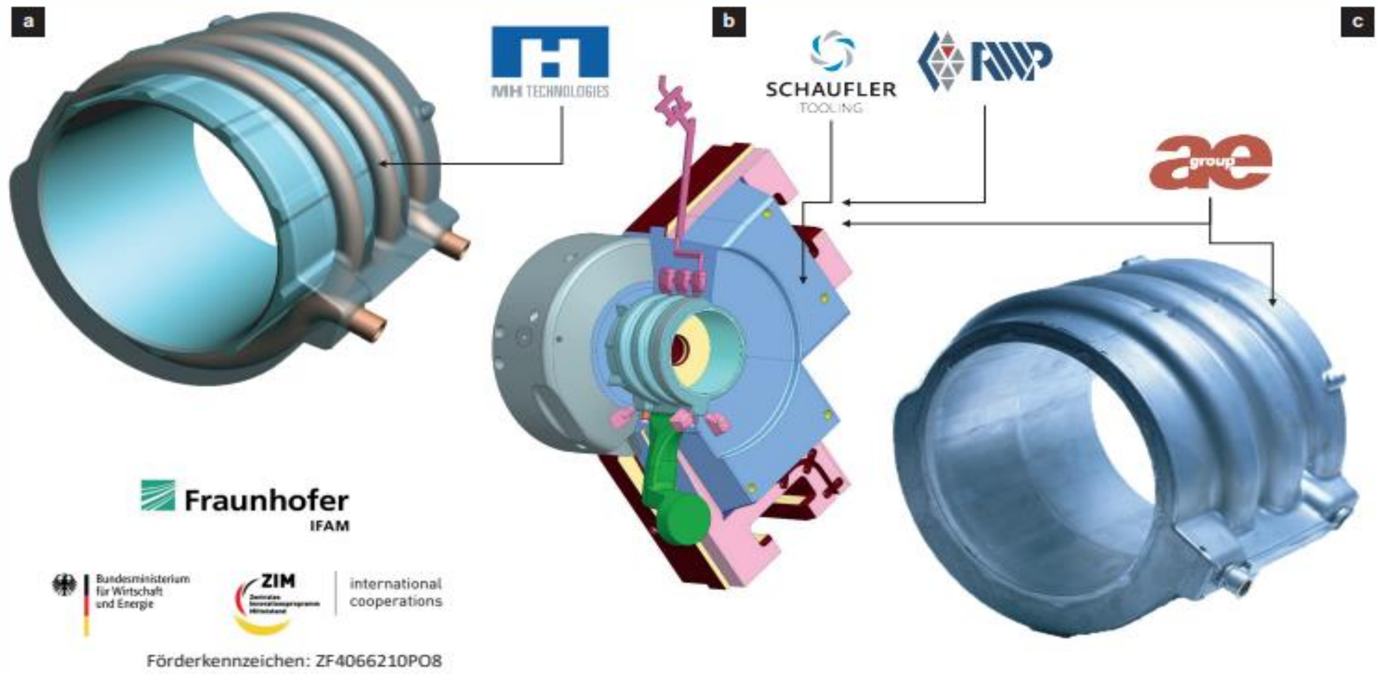


Bild 12: a) CAD-Modell des Demonstrators in halbtransparenter Darstellung zur Visualisierung der Lage des Kühlkanals im Gussteil, b) Darstellung des Gussteils mit Gießlauf, Überläufen und Entlüftung in der teilweise ausgeblendeten Form und c) beispielhafte Abbildung des Gussteils selbst. Der Innendurchmesser des beidseitig offenen Zylinders beträgt ca. 140 mm.

Image 12: a) CAD model of the demonstrator in a semi-transparent representation to visualize the position of the cooling channel in the casting, **b)** Representation of the cast part with pouring runner, overflows and ventilation in the partially hidden form and **c)** exemplary illustration of the cast part itself. The inner diameter of the cylinder, which is open on both sides, is approx. 140 mm.

None of the probes compared in this study has been given a surface treatment or other measures to support the formation of a metallurgical connection between the insert and cast. Accordingly, the transition area between the components also shows a clear gap in some areas. As an example, this can be seen in Image 11, which is also showing the influence of this effect on the effective transferred heat flow. According to the relationship shown, this depends on the heat transfer coefficient as well as on the actual contact area. Since the latter in the present case cannot be determined directly, the effective heat transfer coefficients given in Figure 10 also include the effects of a not full-surface transition zone.

Demonstrator

The knowledge gained on the basis of the test geometries was transferred to a demonstrator component at the end of the project, which has the typical geometry of an electric motor housing and a helical cooling channel of approx. 1400 mm in length with an outer diameter of 14 mm and a wall thickness of 2 mm. This will be supported on the inside and fixed by an extruded profile, both variants with spot welded connection of the pipe to the support profile as well as with just a pushed-on pipe were examined. The constructive design of the necessary adaptation of the mold provided by ae group ag was carried out by Schaufler Tooling based on casting simulations from RWP GmbH. Constructive solutions for inserting and fixing the pipes were

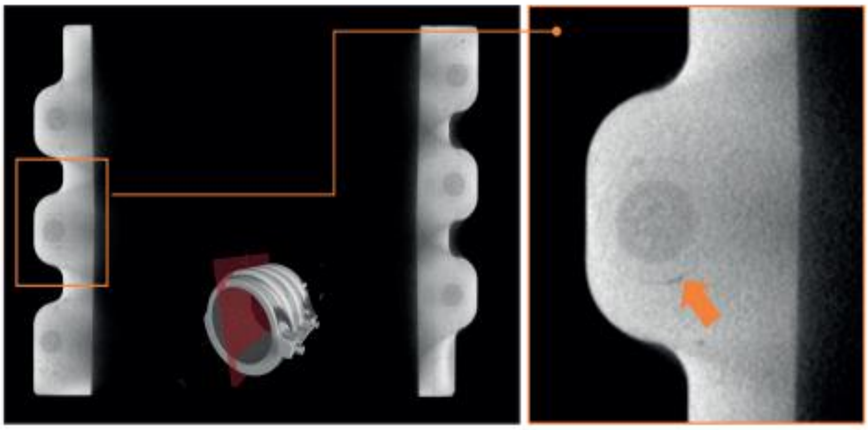


Image 13: CT-shot of the demonstrator with clearly visible gap between pipe and cast (compare enlarged detail on the right). The embedded picture shows the position of the cutting plane

also developed by Schaufler Tooling GmbH. Sampling and parameter optimization were carried out by ae group ag. **Image 12** illustrates the location of the pipe and the support profile within the casting based on a CAD model with semi-transparent cast material and contrasts it with a real cast of the component. As already done during investigations, several components with different parameter combinations were identified and casted at ae group ag. Recompression pressure (200-1200 bar in steps of 200 bar), the Pouring piston speed (2.5 and 4 m / s) and the preheating temperature of the Insert (100 and 200 ° C) were varied. The evaluation of these tests is still ongoing and not fully completed. The casting tests carried out at the ae group ag's Nenterhausen plant were consistently successful. The comparison of the components showed an increase in the component mass with increasing casting pressure, which can be explained partly due to the better recompacting or feeding of the cast matrix, partly due to the stronger compression of the pipes at higher pressure (see Fig. 5). Independent from pressure the support profile was provided with a draft central molding area in all cases so a real component will require post processing. **Image 13** contains various CT images of a casting. The images were taken at the Fraunhofer Development Center for X-ray Technology (EZRT) a resolution (voxel edge length) of carried out approx. 160 µm. The resolution does not have the typical gap dimensions which were found in the test components. Nevertheless, the CT images also show the presence of gaps in case of the demonstrator. Relocations of the cooling channel can also be seen, for example by comparing the distance between the pipe cross-section at the top left and the outer wall of the cast part with the cross-sections on the left in the middle and at the bottom.

Summary

The results of the CoolCast project prove the feasibility and above all also the predictability of the deployment of the ZLeak Tube technology in die casting. This new solution can be used to implement media-carrying channels based on aluminum tubes and hollow profiles in die-cast components. This opens up promising prospects for the production of central components of the electric drivetrain, which require exact temperature control. The stability of the pipes could be used for recompression pressures up to 1200 bar. Those come with a slight decrease in diameter of the cast pipe, however the magnitude of this effect as well as those caused by the flow and the resulting thermal Relocation of the Pipes can easily be predicted using the casting simulation and can therefore be included in the cast part design. From a lightweight construction point of view, it is of importance that the stability of the pipes within the limits considered does not depend significantly on the wall thickness. If you go from the casting technology. If a certain amount of casting thickness is required, material can be saved here or with the same external dimensions inner cooling channel diameters can be enlarged. At the same time the proven producibility of pipes with bending radii of 1.5 times the diameter (depending on the material) in this project gives the designer the freedom of design. There is further potential for optimization with regard to the thermal connection of the cooling channels to the cast part. The results show already that the usage of same materials has advantages over steel-based solutions, the comparison with theoretically possible heat transfer coefficients with an optimal connection, shows that with regard to the thermal behavior of the transition zone further improvements are possible. The future realization will increase the attractiveness of the featured technology, which already fulfills the target requirements at this stage.

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Literature

[1] Giesserei 105 (2018), [No.3], pp. 32-37
[2] Heiselbetz, C.; Feikus, F. J.; Kniewallner, L.; Rafetzeder, M.; Luszczak, M. Challenges posed by E-Drive components:Casting solutions. Conference fee Casting technology in engine construction 2017, 01.-02. February 2017, Magdeburg.

[3] SAE International Journal of Engines 2(2009), [No. 1], pp. 314-326.

[4] Lahaye-Geusen, M. Light and compact housing for eight-speed automatic transmission - lots of functionalities in a small space.

https: //automobilgestaltung.industrie. de / general / much-function-in-little space / (accessed 19.07.2021)

[5] Foundry experience exchange 3/4 (2013) pp. 6-9.

[6] www.mhrnd.com (accessed July 19, 2021)

[7] Kim, J. S.; Yoo, J. High Pressure Die Casting Core and Preparation Method of High Pressure Die Casting Core. Korean patent KR101965669B1, date of Publication 04/04 2019.