

Article

Influence of High-Pressure Die Casting Process Parameters on the Compound Strength of Hybrid Components with Undercut Sheet Metal

Lukas Bruckmeier ^{1,*} , Aron Ringel ², Uwe Vroomen ¹, David Bailly ² and Andreas Bührig-Polaczek ¹

¹ Foundry Institute (GI), RWTH Aachen University, Intzestraße 5, 52072 Aachen, Germany; u.vroomen@gi.rwth-aachen.de (U.V.); sekretariat@gi.rwth-aachen.de (A.B.-P.)

² Institute of Metal Forming (IBF), RWTH Aachen University, Intzestraße 10, 52072 Aachen, Germany; aron.ringel@ibf.rwth-aachen.de (A.R.); david.bailly@ibf.rwth-aachen.de (D.B.)

* Correspondence: l.bruckmeier@gi.rwth-aachen.de; Tel.: +49-(0)-241-80-95903

Abstract: Reducing the weight of parts through lightweight designs impacts CO₂ emissions, especially in the automotive and transportation sectors, which have significant fuel and electric energy consumption. Using multi-material design approaches, specific material properties can be combined to achieve effective lightweighting. Commonly used metals include aluminum, which is known for its high specific strength, and steel, which is valued for its strength and structural integrity. However, joining aluminum and steel presents challenges given their different thermophysical properties and the potential formation of brittle intermetallic phases, making common joining techniques like fusion welding unsuitable. In this study, a hybrid casting process for the production of a complex workpiece from dissimilar materials was investigated. Aluminum was die-cast around a steel sheet insert. Surface structures with undercuts on the steel sheet were applied through modified cold rolling, allowing molten aluminum to flow into the channels and interlock during solidification. It was found that elevated temperatures of the melt and tool were beneficial for the interlocking, resulting in a 30% increase in compound strength. Furthermore, a reduction in both the piston position at the changeover point, between the pre-filling and cavity filling, and the melt velocity at the gate reduced the compound's strength by 41% and 30%. Up- and downstream processes did not show any significant influence on the conducted experiments. Based on this, two main detrimental effects were observed: pre-solidification of the aluminum melt and gas entrapment.

Keywords: interlocking; multi-material components; structured cold rolling; high-pressure die casting



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1. Introduction

Multi-material design is widely used in the automotive industry to reduce vehicle weight, meet CO₂ emission targets of internal combustion engine cars and increase the range of battery electric vehicles. One possibility is to combine a high-strength base material with stiffening elements made of light metal. A good example using readily available materials involves a combination of steel and aluminum. The steel provides the necessary strength and ductility, while the aluminum contributes to the properties of the composite with an average strength at only a third of the steel's density. However, their dissimilar metallurgical properties and tendency to form brittle intermetallic phases (IMPs) make the joining of steel and aluminum a challenge [1]. Therefore, alternative joining techniques based on interlocking connections instead of commonly used welding techniques are needed. Furthermore, these techniques need to fulfill the requirements of structural components in automotive applications regarding complex geometries. A near-series casting representing a section of a roof crossmember was selected to test the interlocking connection [2]. The part was designed as a piece of bent sheet metal reinforced via an X-shaped light metal cast structure. In our initial investigations, the aluminum melt was cast around a perforated

steel sheet insert. To improve interlocking, we aimed to build an aerial connection between the interfaces instead of a local one. For this purpose, a multi-pass rolling process suitable for mass production was developed in order to produce channel-like structures with undercuts. These structures were filled with aluminum melt using a high-pressure die casting (HPDC) process, forming an interlocking connection as the aluminum solidified in the undercut channels. The focus of this study was to develop a process for the production of the previously mentioned structural part and to analyze the influencing factors of the HPDC process. Since the joint's strength is crucial for possible applications, the static and dynamic strength of the die-cast hybrid components was tested.

2. State of the Art

To overcome the problems of common methods of joining steel and aluminum, new joining processes have been developed [3]. Common metallurgical bonding techniques, like brazing or welding, bring the risk of brittle IMPs when joining different materials [4]. Solid-state welding processes offer the possibility of avoiding the problems of heat-affected zones. In friction stir welding (FSW), a rotating pin is used to cold weld sheet material at the edges [5]. In cold roll bonding, the sheet material can be joined at the surfaces via a high interfacial pressure [6]. Both processes require large plastic deformations and are usually used for parts with simple geometries, such as sheet metal or tubular materials [7]. Mechanical joining processes interlock materials via deformation [8]. While mechanical fastening processes, like riveting, need auxiliary joining parts [9], processes like clinching and hemming avoid these [10,11]. Nevertheless, these processes are mainly used for joining sheet material and need access to tools in the joining area. Especially, rivets and clinches, the connection is spot-shaped.

Hybrid casting is a process where two different materials are joined, and at least one material is formed in a primary molding process [12]. This allows a sheet metal insert to be placed in a permanent mold and encased in melt [13]. The geometry of the sheet insert can also be formed, e.g., via bending or deep drawing to achieve more complicated geometries. Furthermore, casting makes complex compound geometries possible and can be designed to cover the joining area. The connection can be created with a metallurgical bond, e.g., via coating the surface of the insert [14]. Alternatively, the joint can be reached via mechanical interlocking. Ucsnik et al. [15] used ball-head pins on the surface of tubes and Joop [16] used a perforated steel sheet as inserts for hybrid casting. In both cases, the pins or holes worked as anchors for the melt once solidified. However, the pins and holes only acted locally.

To overcome this, a surface structure with undercuts was needed, allowing the aluminum melt to clamp over a larger area [17]. Surface structures can be created using ablative processes, such as micro-milling and laser surface texturing [18,19]. Joining methods, like coining or imprinting, can reduce process times and manufacturing costs but are limited in workpiece size as well [20]. Therefore, a continuous multi-pass rolling process was developed by Senge et al. [21] at the Institute of Metal Forming (IBF), which allows for the creation of channel-like surface structures with undercuts (Figure 1).

In the first pass, rollers with a machined surface structure were used to imprint grooves into the surface of a steel sheet. The resulting rectangular ribs were then flattened in a second pass (flat rolling). The tips of the ribs spread horizontally and form an undercut of up to a 50 μm width [22].

The created structures were inserted into an HPDC process at the Foundry Institute (GI) of RWTH Aachen. The strength of the joint depends on the geometry of the structure, especially the width of the undercut [22]. Conducted shear tests showed that the connection was loadable up to 45 MPa. Further studies also investigated the formation of the undercut, observing the formation of an inner fold that might weaken the connection [23]. To further investigate the different joining methods in hybrid casting, an industry-related example part for the high-pressure die casting process was developed by the Foundry Institute (GI) of RWTH Aachen [16]. This part enables the use of a structured and bent steel sheet insert.

In combination with the X-shaped aluminum casting, a complex compound geometry is possible. In addition, the proposed process chain of structural rolling and die casting is suitable for mass production.

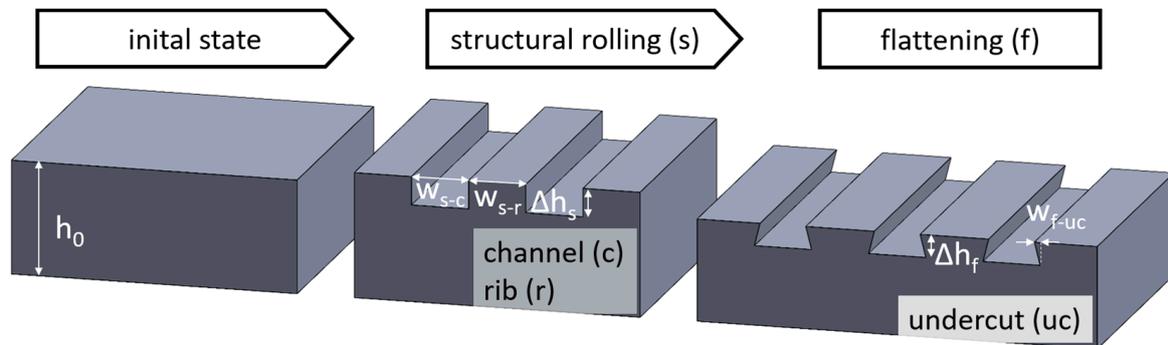


Figure 1. Process scheme for channel-like surface structures with undercuts.

It is generally known that the mechanical properties as well as the flowability of AlSi alloys in high-pressure die casting can be influenced not only via the geometry of the casting but also via the process parameters. Lower pouring temperatures as well as a higher proportion of oxides in the melt can significantly reduce flowability and, thus, mold filling capacity [24,25]. Furthermore, the risk of casting defects, such as cold flow and porosity, and their distribution are affected via the melt velocity during mold filling and the thermal boundary conditions in the shot sleeve after the melt dosing process [26,27].

3. Methods and Processes

The first step in this work was to demonstrate the improvement in the strength of the example parts due to the surface structure. To obtain a comparison between unstructured and structured parts, a fatigue test with dynamic loading was designed for the entire part. The hypothesis was that the surface structure would increase the load bearing capacity and that wider structures would proportionally increase the compound's strength. In the next step, the goal was to determine the influences of varied process parameters in HPDC as well as common upstream and downstream treatment processes on the compound strength. In order to represent a wide range of casting conditions common to the industry, their effect was evaluated via means of an extreme value analysis. During casting, the relatively small channels must be filled with melt. The hypothesis is that the melt and mold temperature, as well as the melt velocity during the filling phase, affect the resulting strength. In addition, the effects of fluctuations in the dosing process and, thus, deviations of the changeover point between the prefilling phase and the mold filling phase were investigated. Regarding the upstream and downstream process parameters, the influence of preheating the insert to be encased in the casting process, water bath quenching of the hybrid part after casting and solution annealing in the form of a T6 heat treatment were investigated. To evaluate the effects on the performance of the hybrid parts, the tensile strength of the joint was measured on specimens of the example part.

3.1. Production of Steel Sheet Inserts for HPDC

The sheet insert was made of 2.0 mm thick DC04 steel to meet the strength and ductility requirements for the base material. Sheets of a 160 mm width and a 475 mm length were used for structural rolling. Rolling was conducted on a roll forming machine (P3.160; Dreistern GmbH & Co. KG (Schopfheim, Germany)). Since the cast metal is applied on both sides, the channel structures were imprinted longitudinally in the central area on both sheet surfaces (Figure 2).

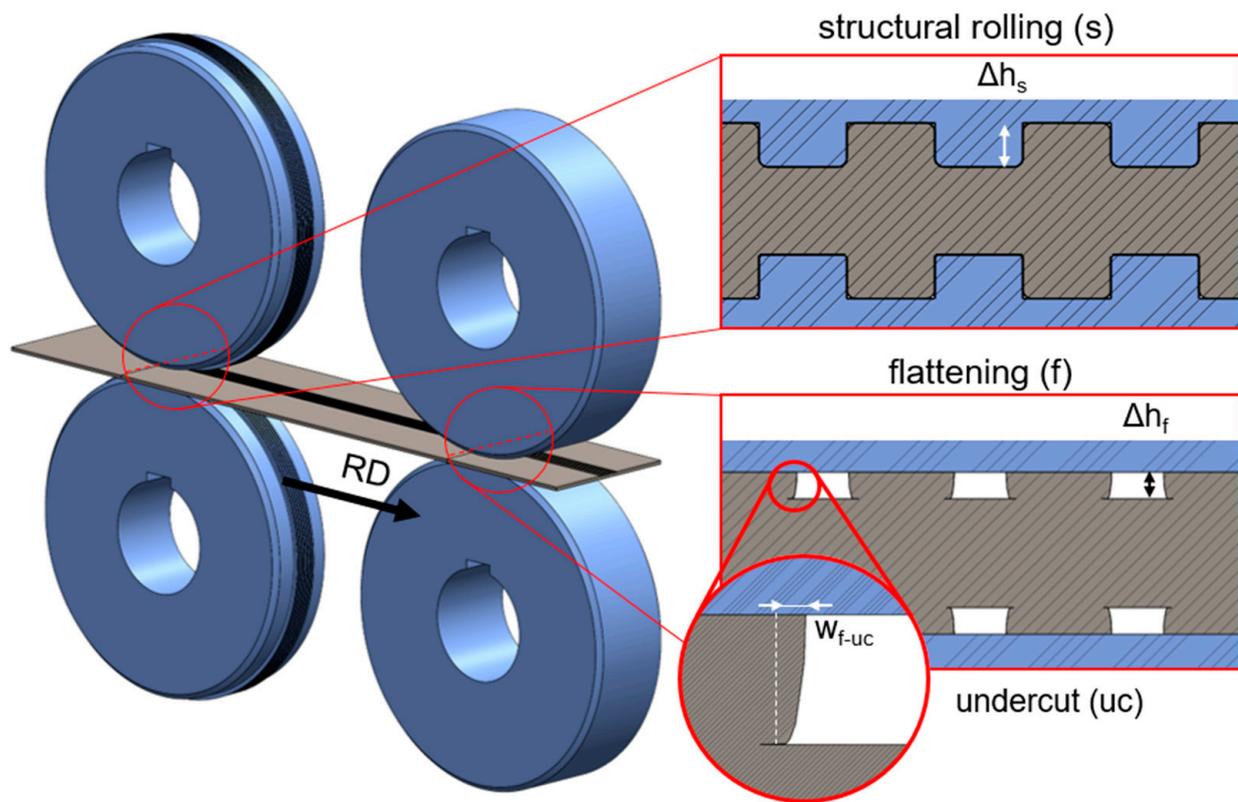


Figure 2. Process scheme of double-sided structural rolling and flattening.

For the first pass, two profiled rollers with 92.5 mm radius and 13 mm structure width were used. The roll profile had seven ribs and six channels, each with a width of 1.0 mm and a depth of 0.5 mm, and radii at the rib edges of 0.05 mm (bottom) and 0.10 mm (top). Optionally, an intermediate structuring step was performed to create wider structures of 25 mm width. The optional rollers additionally imprinted three ribs and channels on each side of the existing structure. The roll profile had the same rib and channel geometry as the first pass. Two rollers with a radius of 93.0 mm were used for the flattening pass at a rolling speed of 5.8 m/min. In the first pass, channels of an approx. 479 μm depth (Δh_s) were imprinted into the sheet surface. The resulting ribs were flattened, resulting in an average channel depth of $\Delta h_f = 333 \mu\text{m}$ and an average undercut width of $w_{f-uc} = 58 \mu\text{m}$. The geometry measurement was conducted on cross-sectional specimens using a Keyence VHX-7000 (Osaka, Japan) digital microscope.

After structuring, the plates were roller levelled and two sheet inserts of 109 mm \times 203.5 mm were cut from each plate with a waterjet (Figure 3a). The cut specimens were die-bent on a press brake (Trumpf TrumaBend V50; Ditzingen, Germany) into their final shape (Figure 3b). The final geometry required four bending operations, with bending angles of 82° and 133°, twice each. A punch with a radius of 5.0 mm and a die with an opening of 16 mm were used. After bending, the edges at the bending were deburred at the bending curve.

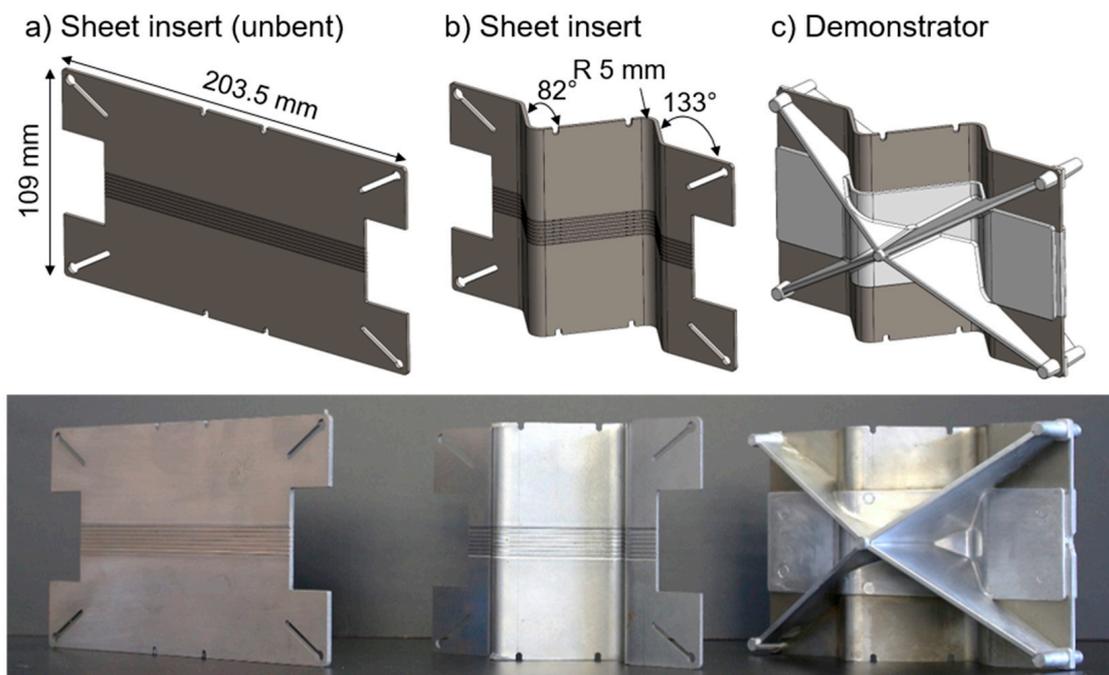


Figure 3. Figure of the cut insert geometry (a), bent insert (b) and hybrid casting (c).

3.2. High-Pressure Die Casting of the Hybrid Part

The hybrid casting trials were performed in a modified version of the high-pressure die casting tool used by Joop [16], which represents structural castings from automotive applications with complex geometric conditions, such as a roof cross-member profile. In order to provide optimal conditions for a hybrid of cast aluminum and steel sheet, the existing hole geometry was optimized using casting simulation software (MagmaSoft 5.4) to achieve a more uniform filling of the die and, thus, reduce the risk of casting defects (Figure 4). Furthermore, the design of a region without a central hole pattern for the melt flow in the sheet metal insert was achieved. This significantly reduced the interference of side effects, such as melt penetrating through the insert. In addition, this central region represents an area where the compound strength can be related solely to the surface structure.

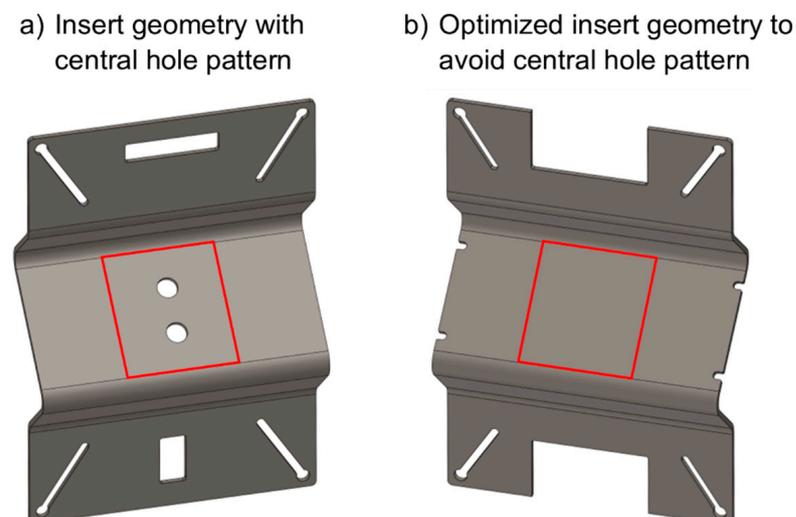


Figure 4. Comparison between original insert version (a) [16] and optimized version for the production of compound test specimens (b).

The stiffening structures were cast from an AlSi10MnMg primary alloy, which has high specific strength but low ductility without heat treatment. The chemical composition is given in Table 1.

Table 1. Chemical composition of the AlSi10MnMg.

Element	Si	Fe	Cu	Mn	Mg	Zn	Ti	Sr
[wt. %]	11.3	0.15	<0.02	0.61	0.39	<0.01	0.15	0.016

The tests were carried out on a vacuum-assisted Bühler H630-SC (Uzwil, Switzerland) cold-chamber high-pressure die casting machine with a nominal locking force of 6900 kN. The aluminum alloy was degassed to a density index smaller than 1.0 to minimize hydrogen content. Oil was used as thermoregulation fluid for both the shot sleeve and the die. The boundary conditions for the casting trials are shown in Table 2.

Table 2. Boundary conditions for the conducted casting trials.

Parameter	Initial Condition
Alloy	AlSi10MnMg
Shot weight	1185 g
Melting temperature	760 °C
Temperature holding furnace	720 °C
Initial temperature shot sleeve	220 °C
Initial temperature die	200 °C
Average cycle time	110 s
Intensification pressure	450 Bar
Plunger diameter	60 mm
Active shot sleeve length	417 mm
Shot sleeve filling level	40%

The Design of Experiment (DoE) carried out is shown in Table 3. To minimize the risk of interactions between configurations within the DoE, the set of five start-up parts was used to provide near-steady-state boundary conditions for the process setup.

Table 3. Design of Experiments to analyze the influences of the HPDC process parameters and up-/downstream processes.

ID	Melt Temperature	Die Temperature	Melt Velocity at Gate	Changeover Point	Upstream/Downstream Processes
1 *	720 °C	200 °C	40 ms ⁻¹	265 mm	Air quenching
2	760 °C	250 °C	40 ms ⁻¹	265 mm	Air quenching
3	720 °C	200 °C	20 ms⁻¹	265 mm	Air quenching
4	720 °C	200 °C	60 ms⁻¹	265 mm	Air quenching
5	720 °C	200 °C	40 ms ⁻¹	240 mm	Air quenching
6	720 °C	200 °C	40 ms ⁻¹	280 mm	Air quenching
7	720 °C	200 °C	40 ms ⁻¹	265 mm	Pre-heating insert
8	720 °C	200 °C	40 ms ⁻¹	265 mm	Water quenching
9	720 °C	200 °C	40 ms ⁻¹	265 mm	T6 heat treatment

* Reference.

In the first five configurations, the process parameters of HPDC are varied to analyze the influence of melt and cavity temperature (ID 2), melt velocity at the gate (ID 3, 4) and the changeover point from pre-fill to cavity-fill (ID 5, 6). The remaining three configurations are used to determine how common upstream and downstream processes in HPDC affect the part. As an upstream process, the sheet insert was preheated to a temperature of 400 °C prior to die casting (ID 7), while as a downstream process, water quenching (ID 8) and a T6

heat treatment (ID 9) was performed. For the T6 heat treatment, the demonstrator parts were solution annealed at 520 °C for 1 h and artificially aged at 160 °C for 6 h.

3.3. Casting of the Hybrid Component and Preparation of the Tensile Testing Sample

For each process variation of the following tests, a set of seven parts was taken from the batch of castings. These seven parts were prepared and tested. To quantify the static bond strength, a sample is taken from the casting for tensile testing. To eliminate influencing factors from the overall complex geometric conditions, the sample section is cut from the center of the casting as shown in Figure 5. A horizontal bandsaw with controlled hydraulic feed was used to apply minimal force. The length of the structure varied in the range of 50 ± 3 mm due to the semi-automatic sawing process. Each specimen was individually measured to compensate for any effects on the compound's strength. Centrally located holes were then milled in the aluminum casting to allow application of the test force normal to the bond surface (Figure 6). For dynamic testing, the castings were separated only from the gating system and the overflows. No other mechanical process was performed prior to testing. The length of the structure within the demonstrator part is approximately 153.5 mm.

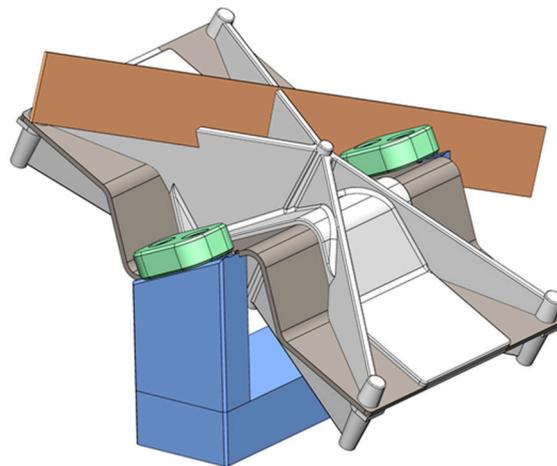


Figure 5. Tensile test specimen cut via horizontal band saw.

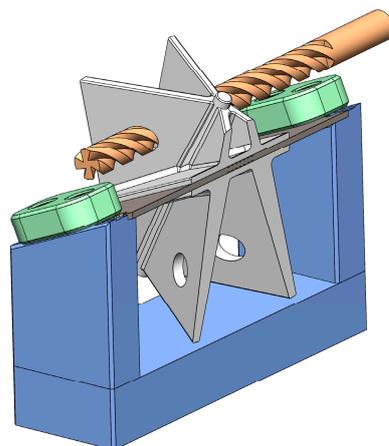


Figure 6. Milling holes in the tensile sample for the test fixture.

3.4. Static and Dynamic Testing of the Demonstrator Part

Dynamic testing was performed on a 250 kN Schenk (Darmstadt, Germany) servo-hydraulic machine. Demonstrator parts without (reference) and with 13 mm and 25 mm wide surface structures were tested, all cast according to ID 1 (Table 2). In the case of the

unstructured part, the materials were bonded only through the holes in the sheet steel insert. The demonstrator part was placed in a three-point bending test fixture, as shown in Figure 7. The specimen was tested at a stress ratio of 0.1 with a loading force alternating between 3 kN and 30 kN at a frequency of 20 Hz until failure. Crack initiation was detected via an increase in displacement.

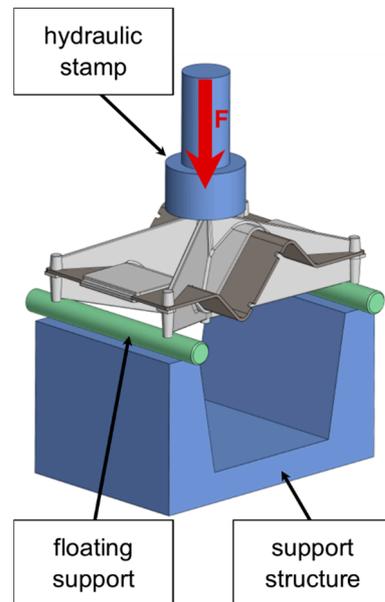


Figure 7. Demonstrator part in dynamic test.

For static testing, the specimen was installed in a Zwick Z100 (Ulm, Germany) tensile tester, with custom-made specimen grips and loaded to failure (Figure 8). Prior to testing, the sample was preloaded with 10 N. A travel speed of 0.5 mm/min was used for the tensile test. In this test setup, only parts with structured surfaces could be tested.

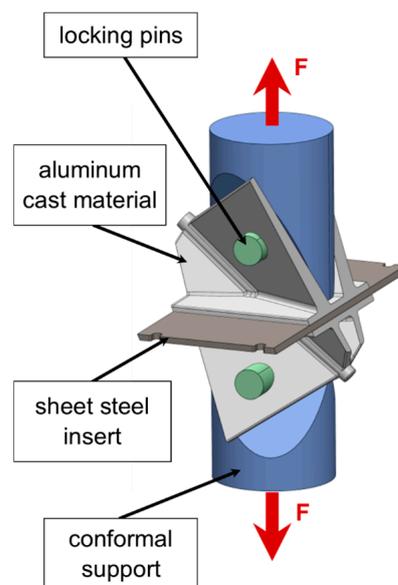


Figure 8. Cut demonstrator part in tensile test.

4. Results and Discussion

For each group of dynamic and static tests evaluated, the standard deviation of the measurement results was added as an error bar in the positive and negative directions. The influence of the surface structure on the strength of the part can be seen from the dynamic test results in Figure 9. Failure of the parts was due to fracture of the die-cast aluminum rather than failure of the interlock. A demonstrator part joined only via the interlock through the holes in the sheet steel endured an average of ~14,500 load cycles. A 13 mm wide surface structure increased the load bearing capacity by around 55%. With the 25 mm wide surface structure, approximately 17% more load cycles could be achieved. This demonstrates the significant contribution of the surface structure to the integrity of the part.

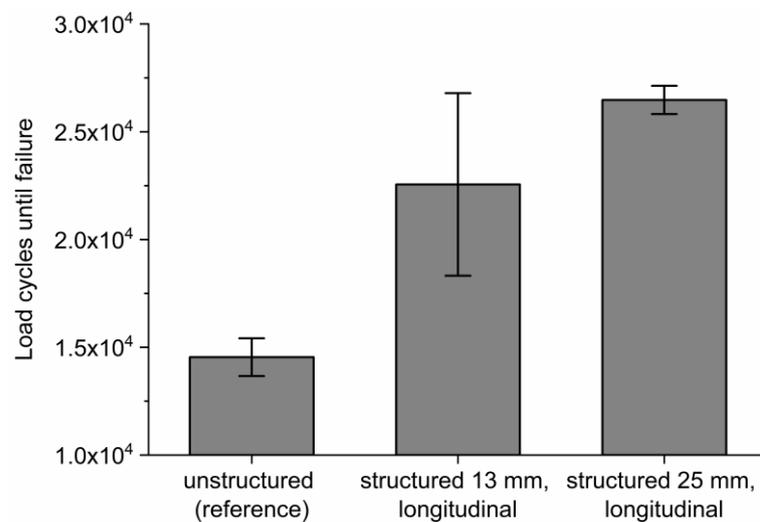


Figure 9. Influence of surface structure on the bending cycles to failure.

Failure of the interlock was observed during tensile testing of the cut specimens. No fracture of the base materials occurred, but the interlocking failed due to the deformation of the structure and the sliding of the interlocked surfaces against each other. For evaluation, the measured mechanical load from the tensile test is converted to an equivalent stress value, σ_{eq} . The length of the specimen after sawing and the maximum width of the insert structure used result in a rectangular interlocking area that is used for the stress calculation. Microscopic analysis (Figure 10) showed that the outermost channels of the surface structure did not form undercuts on the outside (Figure 10, circles). Therefore, half of the channel width was subtracted on each side, resulting in a nominal width of 12 mm and 24 mm.

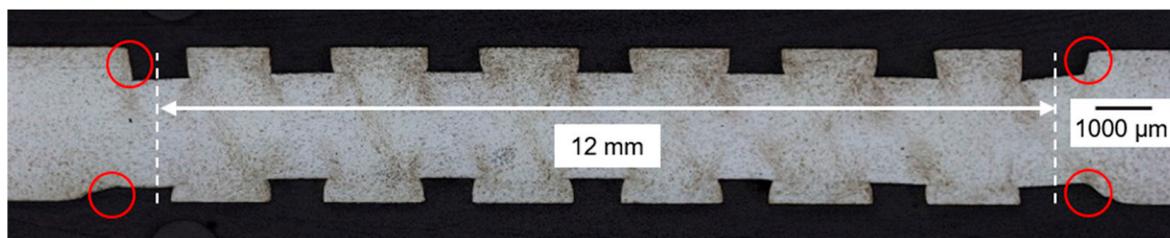


Figure 10. Cross-section view of 13 mm structure. Reduced undercuts for outer channels and 12 mm nominal interlock width.

The results were then compared to the strength of the reference parameter set. The reference parameter set (Table 3, ID 1) produced a mechanical interlock with an equivalent resilience of $\sigma_{eq} = 6.9$ MPa. The results in Figure 11 show that increasing the melt and mold temperature by 40 °C and 50 °C, respectively, improved the compound strength by 30%. The observed result is in line with expectations, as it is known that the flowability of AlSi alloys used in HPDC increases with higher superheat, allowing the melt to fill the narrow channel structures more easily [28].

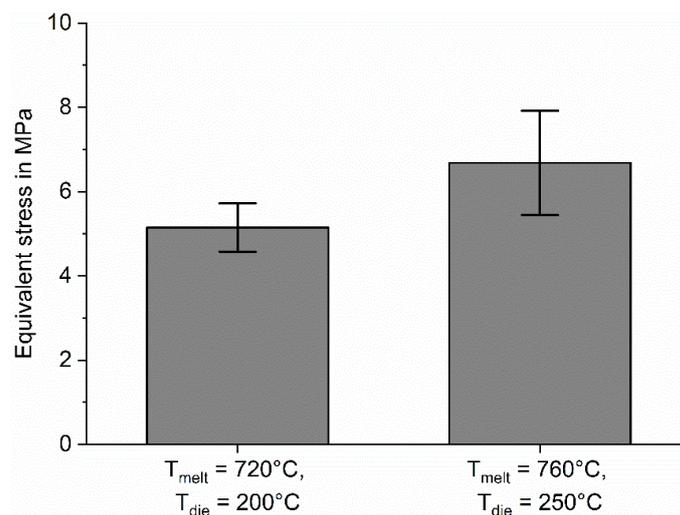


Figure 11. Influence of melt and die temperature on the compound strength.

As shown in Figure 12, a reduction in melt velocity to 20 ms^{-1} at the gate resulted in a significantly lower strength. The reason may be that a lower velocity can cause premature solidification effects in the gate area [29].

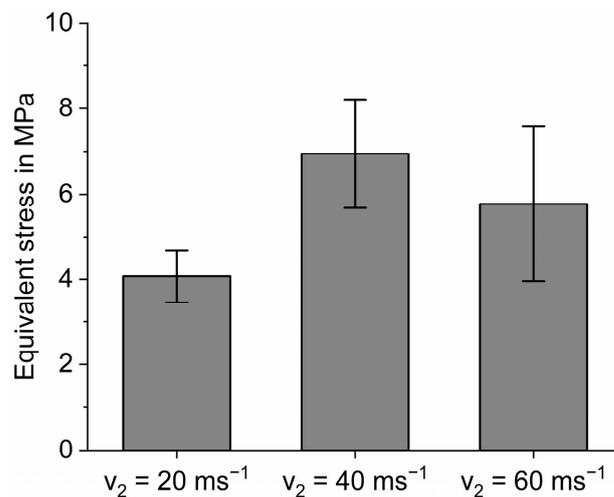


Figure 12. Influence of gate velocity on mechanical compound strength.

This reduces the potential for the melt to penetrate the structured surface of the insert (Figure 13c). The resulting test specimens showed a 41% reduction in resilience. A similar but smaller 17% reduction in equivalent resilience was observed at a high melt velocity of 60 ms^{-1} at the gate. Clearly, the chosen velocity exceeded the optimum for rapid cavity filling, which, according to Karban et al., can cause additional microporosity in the part (Figure 13b) [30].

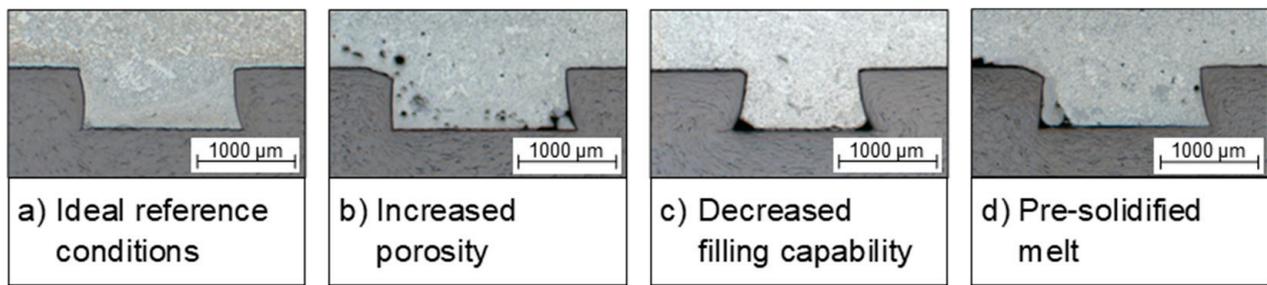


Figure 13. Micrograph sections showing ideal undercut channel filling conditions (a), increased porosity levels in the channels (b), sections with reduced filling capacity of the melt (c) and sections with partially prefilled channels (d).

As shown in Figure 14, especially an early changeover point significantly reduced the strength of the compound by 29%. Because the amount of melt varies slightly during the dosing process, the theoretical “Chamber Full” moment also varies in reality. By accelerating the plunger earlier, residual air in the shot sleeve can be partially included in the melt flow. As a result, the risk of externally solidified crystals increases [31] and the filling quality of the structures degrades. Postponing the changeover point closer to the position of “Metal at Gate” resulted in only a minor reduction of 6%, indicating that there was no significant prefilling of the channels (Figure 13d).

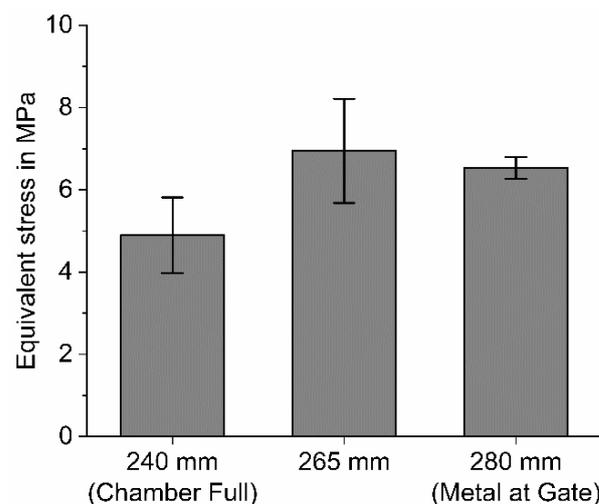


Figure 14. Influence of the changeover point on the mechanical compound strength.

Within the error deviation, insert preheating, water quenching and a T6 heat treatment did not appear to have a significant effect or may slightly degrade the compound strength (Figure 15). The reason appears to be that, except for insert preheating, these processes do not directly affect the filling of the structures with melt. For the preheated insert, rapid cooling was observed after placement in the die, as the temperature difference was quickly equalized by the large mass of the mold. Changes in material properties due to downstream treatments have little effect on the compound strength compared to the formation of the interlock.

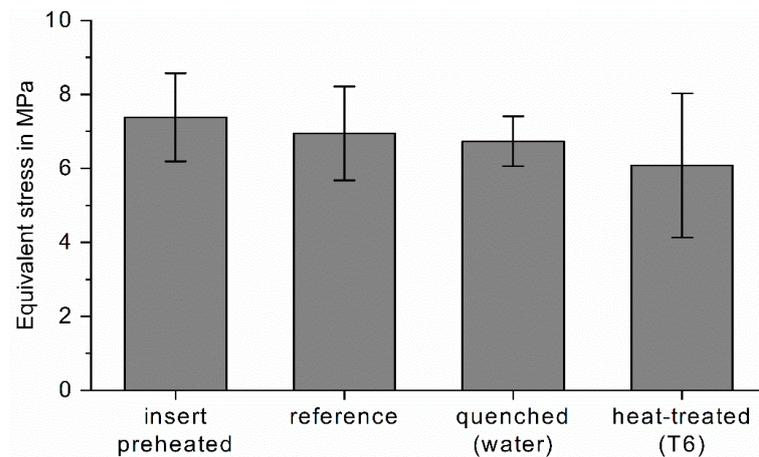


Figure 15. Influence of up- and downstream processes on the mechanical compound strength.

5. Summary and Conclusions

The results show that the compound demonstrator with a mechanical interlock between sheet metal and cast aluminum can be produced via high-pressure die casting and that surface structures can contribute to and enhance the strength of the part. The results are summarized in Table 4.

Table 4. Tensile test results of test samples.

ID	Process Parameter	Equivalent Stress	Reference Comparison
1	Reference—13 mm structure	6.9 MPa	-
	Reference—25 mm structure	5.1 MPa	-
2	Raised melt/die temperature	6.7 MPa	+30% (2)
3	Melt velocity at gate 20 ms^{-1}	4.1 MPa	-41% (1)
4	Melt velocity at gate 60 ms^{-1}	5.8 MPa	-17% (1)
5	Changeover point at 240 mm “Chamber Full”	4.9 MPa	-30% (1)
6	Changeover point at 280 mm “Metal at Gate”	6.5 MPa	-6% (1)
7	Pre-heating insert	7.4 MPa	+6% (1)
8	Water quenching	6.7 MPa	-3% (1)
9	T6 heat treatment	6.1 MPa	-13% (1)

(1) Reference 13 mm structure; (2) reference 25 mm structure.

The results show that deviations in the process parameters can cause various casting defects, resulting in a significant change in the bond strength. Two main effects were observed and the following conclusions were drawn from the results:

- (1) Complete filling of the channel structure is critical to the strength of the compound:
 - Increasing the melt and die temperature reduces the risk of cold flow and increases the ability of the melt to fill the undercut channels, resulting in a higher strength during testing.
 - Significantly lower gate velocities during the mold filling phase and premature changeover points result in poorer channel filling and reduced compound strength.
 - Too high gate velocities also reduce the compound strength via increasing the level of porosity observed in the channels.
- (2) The evaluation of upstream and downstream processes such as insert preheating, post-casting water quenching and an additional T6 heat treatment did not significantly affect the test performance, thus reinforcing the main conclusion (1).

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