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Development of new strategies for the mechanical joining of components made of aluminum die casting

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Abstract. Structures made of aluminum die casting are being used in increasing quantities as well as component sizes for various applications. Due to the size of the components, heat treatment of the cast parts following the casting process is omitted in order to meet dimensional accuracy requirements and reduce production costs. From such an approach, challenges arise with regard to the mechanical joining of these aluminum die-cast structures. On one hand, the absence of heat treatment results in a general decrease in ductility. On the other hand, the increasing size of the components introduces process-related tolerances regarding the quality of the casting, including the presence of air or gas inclusions, and significant variations in ductility within the component. These factors present challenges for mechanical joining technologies, such as the potential risk of crack-related defects during the joining process. For the robust mechanical joining of such materials, the development and validation of suitable joining strategies for aluminum die cast components is presented in this paper. A preparatory step involving localized heat treatment in the joining area is implemented to enhance the suitability of the casting material for mechanical joining. The objective is to generate an improved ductility state in the aluminum die casting material, enabling crack-free joining through self-pierce riveting. Additionally, the formability of the aluminum die casting material is characterized using a specially developed ductility testing method. This allows the prediction of potential crack-related defects during mechanical joining. The methods described are developed using the AlSi10MnMg material in its as-cast state and applied to the self-pierce riveting process.

Introduction

Growing social environmental awareness is forcing the automotive industry to reduce greenhouse gas emissions. To achieve emission-oriented targets, lightweight construction has emerged as a suitable approach. Cast aluminum components are used where high design flexibility is required combined with high structural strength [1]. In recent years, there has been a trend towards increasingly larger structures made of die-cast aluminum, which are replacing complex multi-part structures, such as longitudinal beams, battery housings or rear structures in electric vehicles using giga-casting technologies [2].

Due to the size of the component and the associated time and energy costs, the heat treatment of the cast components that usually follows the casting process is dispensed in order to meet the dimensional accuracy requirements. This in turn results in challenges with regard to the mechanical joining of these die-cast aluminum structures.

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Self-Pierce riveting of aluminum cast materials

Mechanical joining processes are particularly suitable for connecting the cast aluminum structures to the rest of the body, which consists of different materials due to multi-material designs. Self-pierce riveting has established as a robust and efficient process for joining different types of materials [3]. Due to the brittle material properties of cast aluminum materials, cracks can occur when using the self-pierce riveting technology [4]. Depending on the application, these cracks can reduce the corrosion resistance of the joint [5]. Process and tool parameters can be adjusted to minimize the formation of cracks during the joining process. In [6], it is found that the die contour, especially the die depth, is the main factor in crack initiation during self-pierce riveting in low ductile materials. However, a very influential factor for a specific adjustment of the mechanical properties and thus the reduction of cracking in the cast material is a heat treatment prior to the joining process [7].

Investigations show that the formation of cracks on the joint button can be prevented by suitable heat treatment [7]. The heat treatment primarily affects the energy absorption value and has relatively little influence on the peak force. In addition, the decrease in material strength during heat treatment does not lead to a reduction in joint performance [8].

Due to the immense importance of a prior heat treatment of the aluminum casting material on the one hand and the fluctuating material properties over the entire casting structure on the other hand, two approaches for the robust mechanical joining of such materials are presented in this study. On the one hand, a joint preparation by means of local heat treatment is investigated, which allows a defined ductility state to be generated in the aluminum die casting material and enables crack-free forming joining. Secondly, the forming capability of the aluminum die casting material is to be characterized by using a specially developed ductility testing method. This enables the prediction of possible process-related cracking during mechanical joining.

Ductility testing methods

Different technological tests are used to determine the ductility of metallic materials during forming or joining processes. However, tensile, compression or deep-drawing tests for material characterization are associated with sample separation from the component and cannot be carried out directly on the component during production. For in-process ductility testing on entire components, it is necessary to use a method that can be carried out locally on the component without significantly damaging the structure.

For the reasons mentioned, a punctual test using a flat punch and a die was developed. This type of test allows characteristic ductility values to be determined directly at relevant joints without damaging the component. The test setup consists of a cylindrical punch and a spring-loaded blank holder on the punch side. On the die side, a tool in the form of a hollow cylinder is attached, see Fig. 1. During the ductility test, the punch presses on the test specimen until a defined drop in force is reached. Conclusions about the ductility of the material to be tested can be drawn from the specific characteristic values such as the maximum punch force F_{max} and the associated punch displacement s_{Fmax} as well as the work applied W_{Fmax} (Fig. 1) [9].

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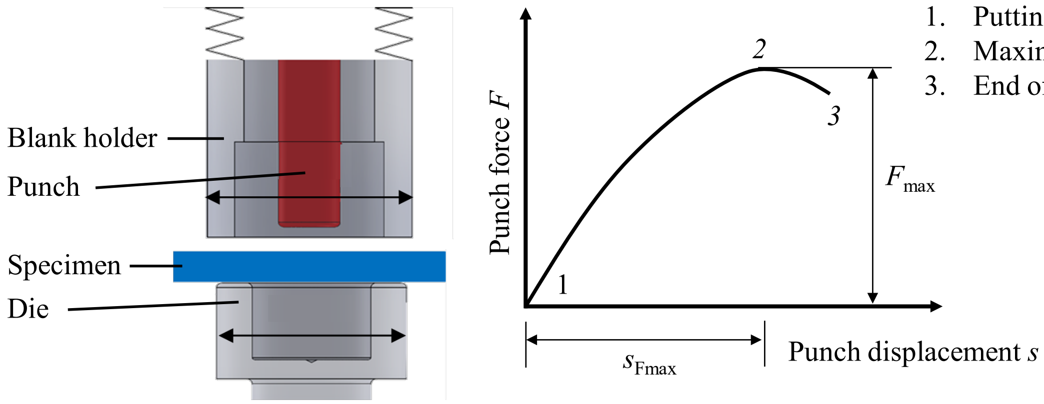


Fig. 1: Experimental setup of the punch indentation test

Local ductility testing

Tool concept. To characterize the ductility of the untreated and conditioned aluminum die casting material, a punctual punch indentation test is used as described. Specific characteristic values such as the maximum punch force and the associated punch displacement are used to identify correlations regarding the ductility of the casting material. The experimental setup of the test is shown in Fig. 2 a). A stamping tool is used that consists of a punch and a spring-loaded blank holder. Thus, it is possible to vary the punch and die geometry as required.

The tool is implemented in a Zwick Z1486 tensile-compression testing machine, which can be seen in Fig. 2 b). It has an extra-wide testing area that allows complete die-cast components to be tested. It is also characterized by precise displacement control. The punch displacement is measured locally using optical measurement systems and digital image correlation.

Fig. 2: Experimental setup of the punch indentation test

Numerical modeling. In order to identify an optimum tool configuration, the ductility test is first analyzed numerically. For the numerical analysis of the ductility test and to optimize the tool geometries, a 2D model was created in Simufact Forming, which can be seen in Fig. 3. It is a rotationally symmetrical setup with rigid tools. For the validation and parameter study, a material model of a wrought aluminum alloy EN AW-6014 T4 has been implemented in order to avoid the influence factor of varying material properties as it is common for cast materials. The implemented flow curve was determined on the basis of layer compression tests and the extrapolation using the Hockett-Sherby hardening law. A combined friction model consisting of the Coulomb friction model and the friction factor model was used to model the frictional behavior. The Coulomb friction coefficient μ was set to $\mu = 0.2$ and the friction factor $m = 0.4$. The macro-mechanical damage criterion according to Cockroft-Latham is used for damage modeling [10]. In this damage model, the first principal normal stress is used to identify critical material states and the plastic work that must be induced in the material to cause damage is calculated. It is possible to specify a damage threshold value so that elements in the simulation are deleted and a crack occurs if this value is exceeded. The damage threshold was set to 0.7. The friction parameters μ and m as well as the damage threshold were adjusted iteratively so that the calculated contour and the force-displacement curve match the experimental data (see Fig. 4).

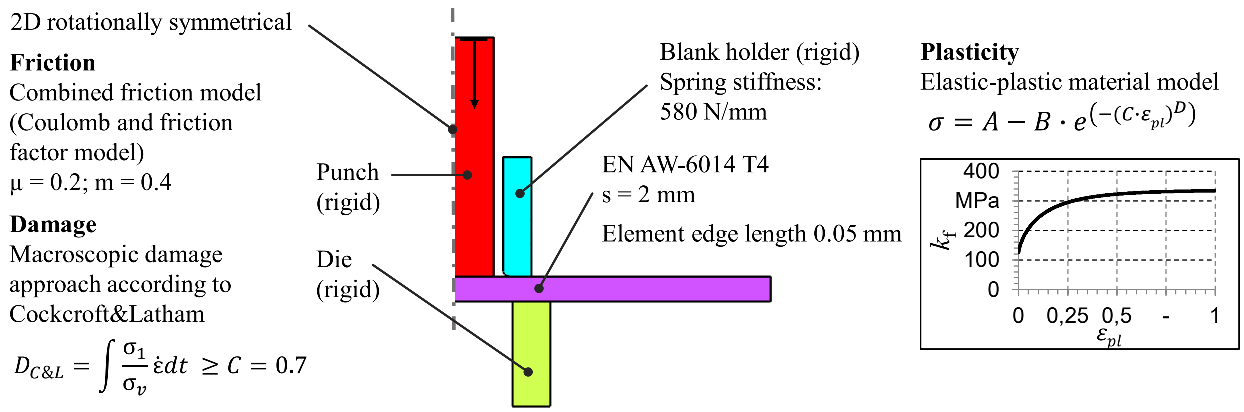


Fig. 3: Numerical modeling of the punch indentation test

Validation. Experimental stage tests were carried out to validate the model using the test setup shown in Fig. 2. The micrographs from the stage tests are shown in Fig. 4 a). In the simulations, the punch displacement was adjusted according to the experimentally measured displacement and the calculated contour in red was compared with the micrograph. In all stages, the calculated contour corresponds well with the geometry from the micrograph. In addition, the numerically calculated force-displacement curves were compared with the experimental data (Fig. 4 b)). The experimental maximum force is 6.0 kN and the numerically determined maximum force is 6.1 kN. The failure displacement also agrees with each other. While the experiment fails at 1.4 mm, the numerical failure displacement is 1.41 mm. As the percentage deviation of the two characteristic values between experiment and simulation is less than 1 % in each case, the model is therefore considered validated.

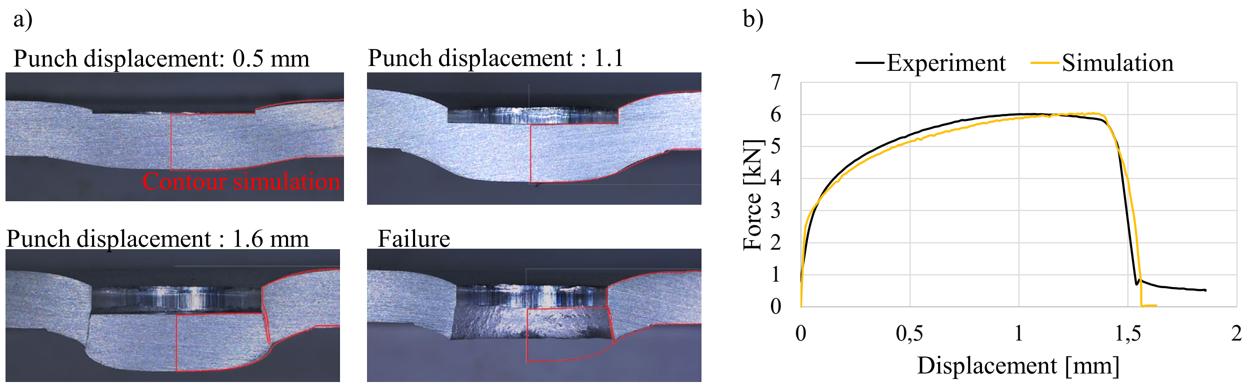


Fig. 4: Validation of the numerical model using geometric contours and force-displacement-curves

The validated model for the punch indentation test was used to analyze influencing factors of the tool geometries on the force-displacement curve behavior. The primary objective is to identify a setup that achieves the longest possible run-out of the force-displacement curve after reaching the maximum force. This should allow enough time to stop the test in a production-accompanying application of this ductility test without the material failing or causing cracks in the component.

As shown in Fig. 5 a), the punch diameter, die diameter and punch radius were varied and various resulting combinations were investigated numerically. Selected force-displacement curves are shown in Fig. 5 a). It can be seen that the maximum force is dependent on the punch diameter due to the squared relationship between the punch diameter and the specimen surface on which the punch impacts. A dependency between maximum force and cutting gap is not recognizable. The failure displacement and the run-out of the force after reaching the maximum is dependent on the punch radius. This is due to a reduced damage input due to reduced shear cutting processes. The larger the punch radius, the longer the run-out until the material finally fails, see Fig. 5 b).

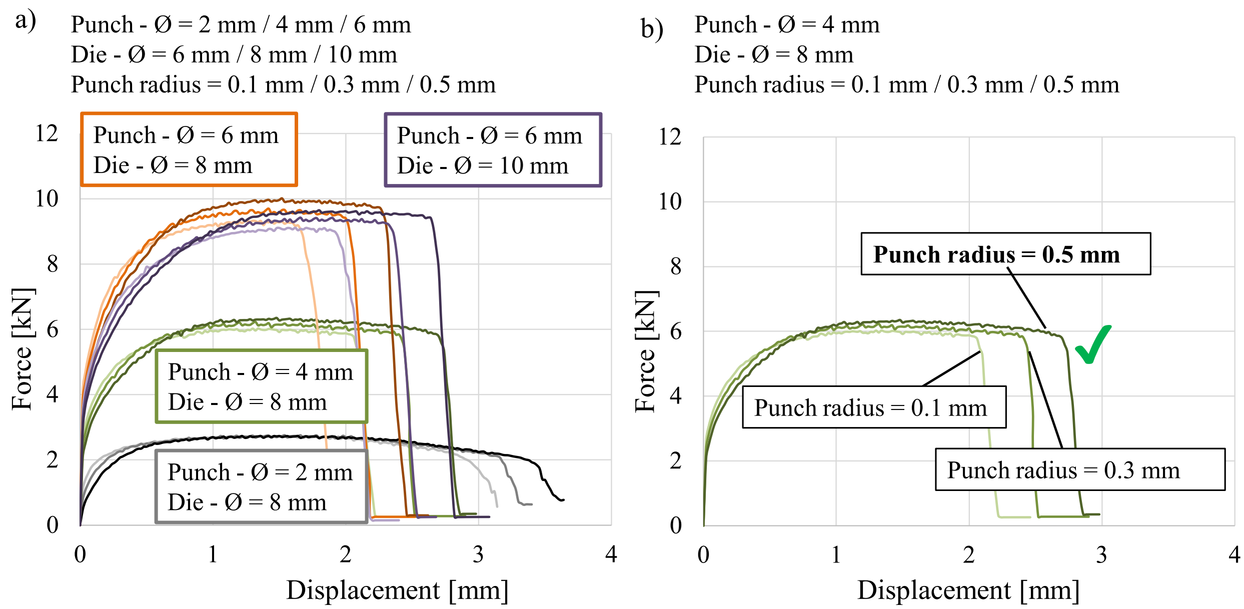


Fig. 5: Influence of tool geometry on the force-displacement curve of the punch indentation test

For the final setup, a punch diameter of 4.0 mm and a die diameter of 8.0 mm were specified. With a smaller punch diameter, it is possible that local material defects such as shrinkage voids near the punch could have a strong influence on the result and this influence is reduced by a larger punch diameter. A larger punch diameter also increases the maximum force and, with regard to the application of the test with mobile tongs, the forces should be kept low. The punch radius was set at 0.5 mm, as this enabled the force-displacement curve to be as flat as possible.

Experimental setup for local heat treatment

Inductive heating. The first investigated method for conditioning the die casting material is inductive heating. A test setup was implemented for this purpose, which is shown in Fig. 6.

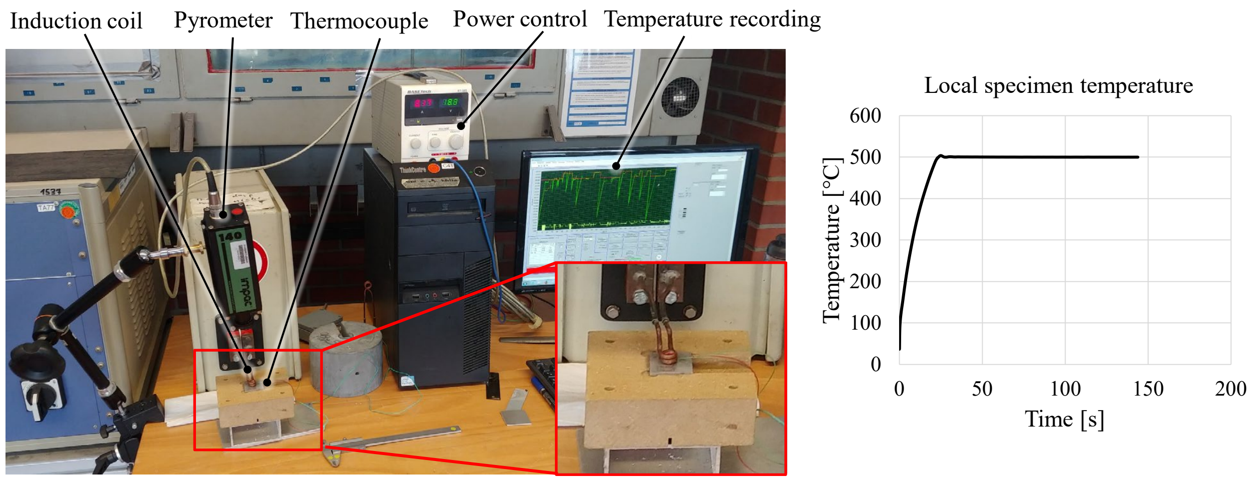


Fig. 6: Experimental setup of the casting materials conditioning via induction heating

It consists of an induction coil with two windings and a diameter of 13 mm, which is connected to a power controller. The coil current is controlled according to the temperature setting. A pyrometer and thermocouples were initially used to measure the temperature. However, the pyrometer had problems with the fluctuating surface properties and associated emissivity of the die-cast material, so the measurement was carried out exclusively with type K thermocouples.

The temperature curve of the sample is shown as an example on the right in Fig. 6. The specimen requires about 25 seconds to be heated to 500 °C and is then held at the specified target temperature for the specified time.

Contact heating. The second method for heating the joining parts is contact heating (Fig. 7). The tool used is an anvil with a heated base, which is heated by heating cartridges. The temperature is controlled using a PID controller and a type K thermocouple is positioned near the surface between the contact area of the joining parts and the underlying heating cartridges.

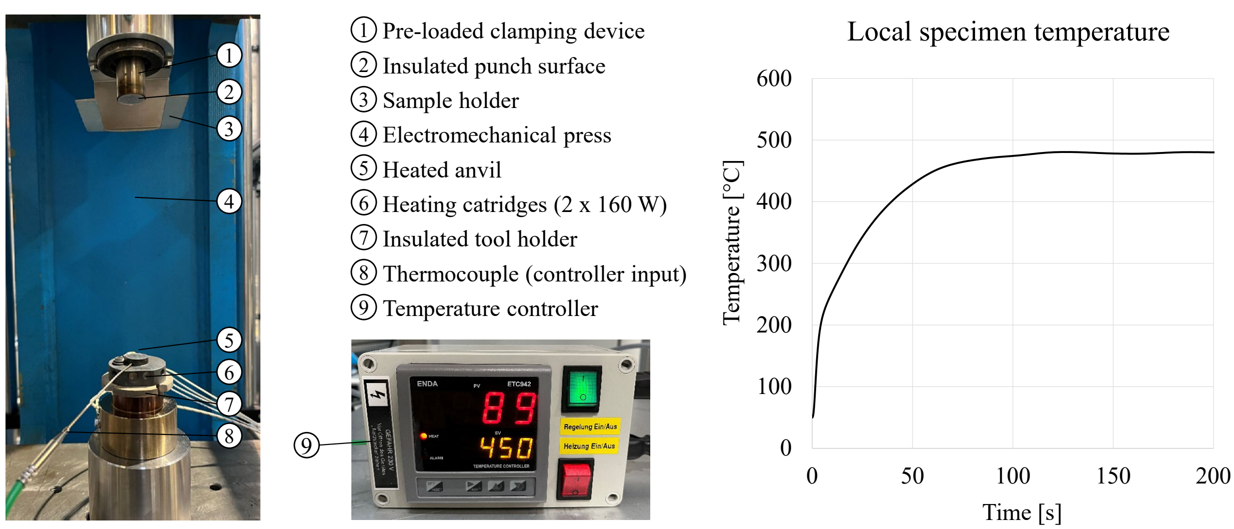


Fig. 7: Experimental setup of the casting materials conditioning via contact heating

This setup offers simplicity and cost-effectiveness compared to induction heating in industrial applications, but it also presents drawbacks in terms of temperature control. The tool temperature decreases upon contact with the joining part, and the temperature drop is subsequently compensated by the controller. It takes time until an equilibrium state is reached where the heat losses to the surroundings are balanced by the contact heating, resulting in a constant temperature in the conditioning zone of the joining part.

The curve shown in Fig. 7 depicts the temperature profile in the casting in the contact zone with the heated tool. For this purpose, a hole was drilled into a sample and a type K thermocouple was integrated for temperature measurement.

The measurement shows that it takes approximately 100 s to reach a nearly constant temperature. The temperature reached at that point is between 475 °C and 480 °C at a tool temperature of 500 °C. Tool temperatures above were not investigated because previous experiments showed that the aluminum material tends to stick to the tool at temperatures above this level. The process duration for contact heating includes the time for temperature ramp-up.

Results

Hardness Measurement and Microstructure. In preliminary investigations, an assessment was made of the temperature range that could lead to a significant alteration in the material properties. The effect of conditioning was examined by measuring Vickers hardness on heat-treated samples, represented in Fig. 8 a).

The analysis of the sample treated by induction heating shows a lower minimum hardness level compared to contact heating with values below 60 HV1. The minimum hardness achieved with contact heating is approximately 65 HV1. The specimens treated by contact heating have become less soft throughout the measured range. In the edge area, they show hardness values close to the untreated state. In the center of the treated area, there is an increase in hardness with induction heating. Partial melting and solidification of the aluminum could be the cause for this effect. This phenomenon can be visible on the surface of the samples as well as occur between the grain boundaries, without being externally detectable [11].

The analysis of a micrograph shows the microstructure before (Fig. 8 b) and after heat treatment (Fig. 8 c) using contact heating as an example. It can be observed that the microstructural state of alpha dendrites of aluminum and the Al-Si eutectic hardly changes due to the heat treatment. A slight homogenization can be noticed, which could be attributed to the diffusion ability of Si caused by the increase in temperature. However, it is assumed that the effect of softening is due to the healing of lattice defects, such as dislocations.

The effect of heat treatment using contact heating appears to be limited to the contact area with the tool, compared to induction heating. This suggests different temperature distributions and disparities in energy input due to heating. Further investigations are needed to understand the specific mechanisms and parameters that lead to this observation.

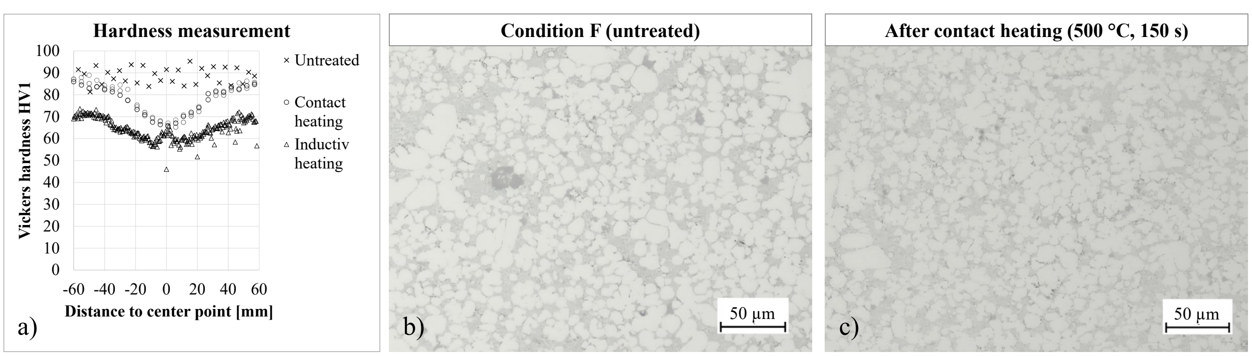


Fig. 8 a) Hardness measurement after heat treatment (T = 500 °C, t = 120 s); Micrograph before (b) and after (c) heat treatment by contact heating (T = 500 °C, t = 150 s), Material: AlSi10MnMg

Ductility test. Measurements were carried out with the above-mentioned final setup of the punch indentation test on casting components in three conditions. The untreated condition serves as the reference, with the input parameter for the heat treatment temperature assumed to be room temperature (RT = 20 °C) in this case. Additionally, two heat treatment conditions are investigated, generated using induction heating. The target temperature in the component was set to 450 °C and 500 °C, with a hold time of 120 s. At this point it should be mentioned that the heat-treated die-cast material is tested in the cold state (RT) with the ductility test and the joining tests are also carried out in the cold state. In Fig. 9, the distribution of individual values for all parameters is shown. It can be observed that F_{max} decreases significantly in the heat-treated state at T = 450 °C. With further increase in temperature to 500 °C, there is a slight increase in F_{max}. This increase could also be related to the local hardening, as indicated by the Vickers hardness values in Fig. 8 a). The maximum punch displacement s_{Fmax} and the forming energy W_{Fmax} until reaching F_{max} also tend to increase with higher heat treatment temperatures up to 500 °C.

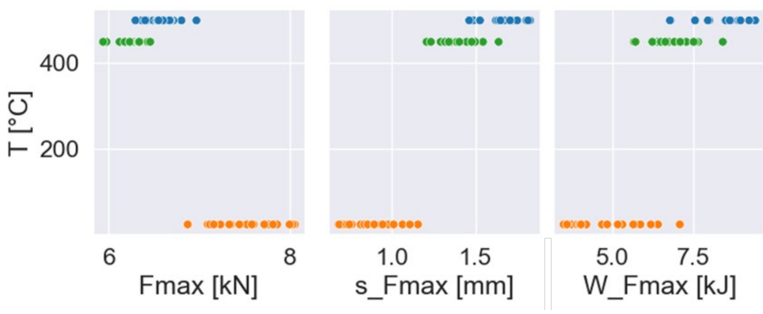


Fig. 9: Parameter distribution of heat treatment temperature and ductility test parameters

Joining experiments. Joining experiments are being conducted using self-pierce riveting. The untreated state of the aluminum casting alloy is used as reference. The findings of the ductility test show that a significant increase in W_{Fmax} can be achieved at a temperature of T = 450 °C and T = 500 °C, see Fig. 9. At a temperature of T = 450 °C, a significant reduction in cracks after joining compared to the reference can be observed. However, the best results are achieved at a setting temperature of T = 500 °C. Fig. 10 shows the SPR joint of a press-hardened steel material with AlSi10MnMg (F) aluminum casting alloy in the initial state of the casting material. Both in the cross-section and in the bottom view, cracks can be observed in the aluminum. The ductility of the material is not sufficient to achieve crack-free joining.

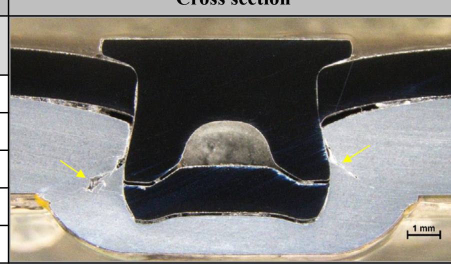
Joining parameters			**Cross section**	**Closing head (bottom view of joint)**
Parts to be joined	Material	Thickness		
Part 1	22MnB5	1.5 mm		
Part 2	AlSi10MnMg F	3.0 mm		
Rivet	HDZ Ø5.5 x 5.0 H6			
Die	Ø11 mm; die depth 1.5 mm			
Joining Force	68 kN			

Fig. 10: Self-pierce riveting without heat treatment of the die cast material

Fig. 11 and Fig. 12 show the result of the joining process after the two heat treatment strategies, applied for T = 500 °C over a time period of 120 s for inductive heating (Fig. 11) and 150 s overall hold time for contact heating at tool temperature of 500 °C (Fig. 12). In both cases, it can be observed that the susceptibility to cracking significantly decreases as a result of the conditioning. The analysis in the cross-section reveals that cracks occur near the rivet foot in the sample treated by contact heating. This is because the temperature-time profile in contact heating is lower, resulting in a reduced effect of heat treatment on the cast material. The presence of such cracks is partially tolerable, as observed in studies on the joining of brittle materials [6]. However, cracks that manifest in larger quantities on the material surface and show a tendency to open up, as depicted in Fig. 10, are considered critical. Additionally, cracks extending from the rivet to the outer side of the joint in the micrograph are also deemed critical and are challenging to detect in a single micrograph.

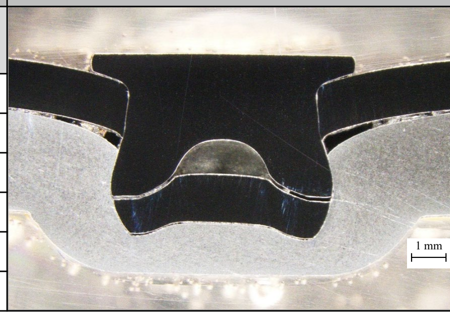
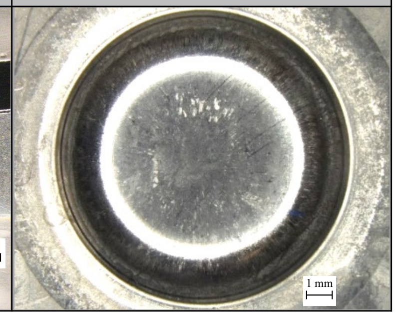
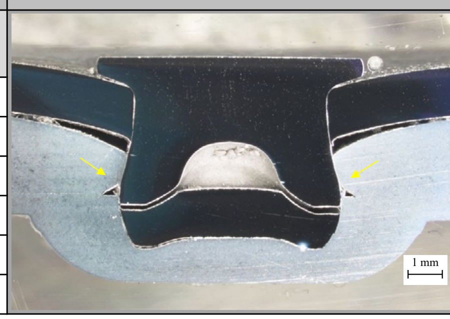
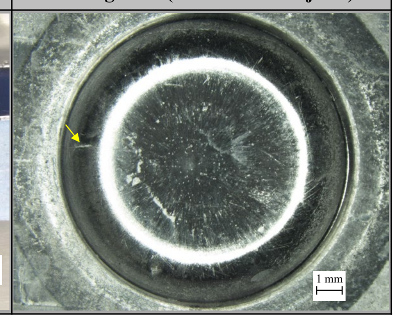
<table>
<tr><th colspan="3">Joining parameters</th><th>Cross section</th><th>Closing head (bottom view of joint)</th></tr>
<tr><td>Parts to be joined</td><td>Material</td><td>Thickness</td><td rowspan="8"></td><td rowspan="8"></td></tr>
<tr><td>Part 1</td><td>22MnB5</td><td>1.5 mm</td></tr>
<tr><td>Part 2</td><td>AlSi10MnMg F</td><td>3.0 mm</td></tr>
<tr><td>Rivet</td><td colspan="2">HDZ Ø5.5 x 5.0 H6</td></tr>
<tr><td>Die</td><td colspan="2">Ø11 mm; die depth 1.5 mm</td></tr>
<tr><td>Joining Force</td><td colspan="2">63 kN</td></tr>
<tr><td>Heat treatment</td><td colspan="2">Inductive heating</td></tr>
</table>

Fig. 11: Self-pierce riveting after inductive heating of die cast material at local temperature $T = 500$ °C

<table>
<tr><th colspan="3">Joining parameters</th><th>Cross section</th><th>Closing head (bottom view of joint)</th></tr>
<tr><td>Parts to be joined</td><td>Material</td><td>Thickness</td><td rowspan="8"></td><td rowspan="8"></td></tr>
<tr><td>Part 1</td><td>22MnB5</td><td>1.5 mm</td></tr>
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<tr><td>Die</td><td colspan="2">Ø11 mm; die depth 1.5 mm</td></tr>
<tr><td>Joining Force</td><td colspan="2">64 kN</td></tr>
<tr><td>Heat treatment</td><td colspan="2">Contact heating</td></tr>
</table>

Fig. 12: Self-pierce riveting after contact heating of die cast material at a tool temperature of $T = 500$ °C

Summary

In this study, two approaches for the robust mechanical joining of aluminum die-cast components were investigated. Firstly, a ductility test in the form of a punch indentation test was investigated experimentally as well as numerically. It was found that the maximum force is dependent on the punch diameter and independent of the cutting gap. Furthermore, the failure displacement and the run-out of the force after reaching the maximum is dependent on the punch radius. Based on these findings, a final setup for the ductility test was determined and tests were carried out on heat-treated samples.

Two different technologies were investigated for the heat treatment of the cast aluminum material. Heating by means of contact heating and induction heating. The comparison of the two strategies showed that both concepts had advantages and disadvantages. Induction heating enabled a fast process with efficient control, but required complex equipment such as fixtures, coils, generators, and control systems, especially for a larger number of joining points. Contact heating using heating cartridges offer a more cost-effective alternative, but the actual temperature achieved in the component could be lower than the set temperature due to energy losses. Therefore, individual adjustment of the setting parameters is necessary to enable crack-free joining of the casting material.

The correlation analysis of the values obtained from the ductility test demonstrated the relationship between the heat treatment and the characteristic output parameters of the ductility test. For example, W_{Fmax} increased when the samples underwent heat treatment. This indicated that heat treatment had an influence on the formability of the material and thus affected the required joining properties.

The ductility test responses to the temperature difference in the range between 450 °C and 500 °C in the parameter F_{max}. In future research, a more comprehensive analysis of the ductility test will be carried out to facilitate quantitative correlations between the occurrence of cracks during the joining process and the output parameters of the ductility test. However, quantifying cracks in the joint poses a challenge as factors such as crack depth and the corrosion relevance of a crack are difficult to determine.

Current work is now investigating the application of local heat treatment to large components. The focus is on a robust process control and demonstrating that local heat treatment does not compromise the dimensional accuracy of the components.

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