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Influence of thermo-mechanical joining process on the microstructure of a hypoeutectic aluminium cast alloy

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Abstract. Requirements of multi-material construction involve adjustments to standard joining techniques. Especially the growing importance of integral cast components poses additional engineering challenges for the industry. One approach to achieve these goals are adaptable joining elements formed by friction spinning. This approach uses friction-induced heat to form customisable joining elements to join sheets for different boundary conditions, even for brittle cast materials. It is possible to react immediately to adapt to the joining process inline and reduce the amount of different joining elements. As the joining partner serve casting plates of the aluminium casting alloy EN AC–AlSi9, which is processed in the sand casting. Joining hypoeutectic AlSi alloys constitutes a challenge because the brittle character of these cause cracks in the joint during conventional mechanical joining. Furthermore, the friction-induced heat of the novel joining process causes a finer microstructure in the hypoeutectic AlSi9 casting alloy. In particular, the eutectic Si is more fine-grained, resulting in higher joint ductility. This study indicates the joining suitability of a hypoeutectic aluminium casting alloy in combination with adaptive manufactured additional joining elements. Here, various mechanical and microstructural investigations validate the influence of the thermomechanical joining technique. In conclusion, the potential of this joining process is presented regarding the joinability of cast aluminium components.

Introduction

In the world of manufacturing technology, a constant state of change due to new requirements from government and society can be identified. The energy and resource efficiency of the production as well as the operation phase of products require an adaptation of conventional and well-known industrial processes [1]. In particular, the automobile industry, which produces many emissions, is continuously faced with new challenges [2]. In response, the industry is increasingly relying on a high-resolution multi-material mix to reduce the masses to be moved and thus the greenhouse gas emissions during the operation phase [3]. To increase productivity and to be able to produce application-adapted components, manufacturers rely on integral aluminium casting components. Aluminium casting alloys of the AlSi(Mg)–system are weldable to a limit, wherefore mechanical joining processes are a suitable alternative [4]. Due to the generally lower ductility and formability of these casting alloys, the connection of such components poses a challenge for joining technology, because the brittle properties, especially the low elongation at fracture, result in cracks in the joint [5].

Classical mechanical joining processes such as self-piercing riveting or clinching require a certain formability of the material, depending on the arrangement of the material [6]. Thermal joining processes such as the established resistance spot welding quickly reach their limits due to the conditional welding work of the cast alloys, the tendency to hot cracks and the resulting low dynamic fatigue strengths [4]. A way to overcome these limitations is to use alternative, ductile aluminium casting alloys that are adapted to the application due to targeted control of the solidification conditions [7]. These are more formable and thus better mechanically joinable than classic alloys. One such alloy is, for example, the AlSi9. Furthermore, there is the possibility to use refinement elements such as Sr or Na to modify the plate-like Si in the eutectic into a fine lamellar microstructure [8]. Hence, the brittle character of the microstructure can be improved into a more ductile, which allows better forming. In addition, to improve the ductility of the cast aluminium components, the (mechanical) joining process can also be adapted to the increased requirements of the joint. One possible group of processes are the thermomechanical joining processes. These processes use the friction-induced application of heat to reduce the materials flow stress locally (temperature is still below the melting temperature) in order to join them [9]. In recent years, friction stir welding in particular has been increasingly used to join aluminium sheets [10,11]. However, this method also reaches its limits with aluminium castings. On the one hand, thin sheets can only be processed to a limited extent, so that the potentially low weight cannot be sufficiently considered. Processes such as flow drilling can also be used with thinner materials, but depending on the arrangement of the materials to be joined, they also require ductile materials in which a viable thread can be formed [12].

A promising innovative thermomechanical joining process is found in the use of adaptive joining elements formed by friction spinning. This approach uses friction-induced heat to produce joining elements from a uniform starting material that are specially adapted to the boundary conditions of the joint. The elements are subsequently used to join sheets with each other. During the joining process, the joining element rotates around its own axis, so that heat is induced when penetrating the materials to be joined and forming the closing head. The friction-induced temperature input into the materials to be joined can be influenced by specific process parameterization in order to change its properties in a targeted manner. [13,14]

The aluminium casting alloy AlSi9 is particularly suitable for adapting the mechanical properties to the requirements of joining processes for this casting alloy by using a targeted cooling strategy. For this purpose, in this work, aluminium casting plates are manufactured by using the sandcasting process and are subsequently joined with a thermomechanical joining process based on adaptively produced friction elements. The input variables of the joining process in the form of the rotational speed and the feed rate are varied and the influence of the variation on the process parameters (temperature, process forces) on the joint (strength, microstructure) is described.

Process principle of the joining using adaptive friction elements

The basis of the versatile joining process with adaptive friction elements is a two-stage process chain with a wide variety of tools and setting variables, which are described in the following. In the first process stage, Friction Spun Joint Connectors (FSJC) are produced from a semi-finished product (d = 8 mm) of the steel C45e. These FSJCs are used in the second process stage to join two different metallic sheet materials. The basis of both process stages is the friction between the die and the semi-finished product or between the FSJC, the sheet metal and the die. The process temperatures of $T > 0.6 \cdot T_S$ within both process stages is set solely on the basis of friction without the use of external heating elements. The heat is required to reduce the flow stress of the auxiliary joining elements.

Process stage 1. Production of friction spun joint connectors (FSJC). In the following, the central requirements of the first process stage are described based on the four sub steps depicted in Fig. 1. A cylindrical bar section of a round rod with a diameter d = 8 mm and length l = 55 mm is first inserted into the collet of a spindle and set in rotation. To ensure continuous rotation, a horizontally arranged milling spindle from the manufacturer Weiss, Mobach Germany with a maximum rotational speed of n_{max} = 14,000 rpm is used. The first process step in the production of the FSJC starts with the positioning is the reaming and thus also the preheating of the rod by a specialised friction spinning tool made of the sintered carbide KX 40 (Co 9 %, WC 91 %). For the investigations described in this publication, the contact surface of the friction spinning tool consists of a cylinder with a diameter of $d = 3$ mm and a tip radius of $r = 1.5$ mm. The friction spinning tool is attached to a cross support, which allows the tool to be moved steplessly to the x and y coordinates shown in Fig. 1. Following positioning, the trajectory required to set a targeted FSJC geometry is executed at a constant rotational speed of $n = 12{,}000$ rpm and a feed rate of $f = 50$ mm/min. The last process step involves reworking the steel FSJC using a conventional turning process to set a uniform shaft diameter of $d_1 = 5.5$ mm.

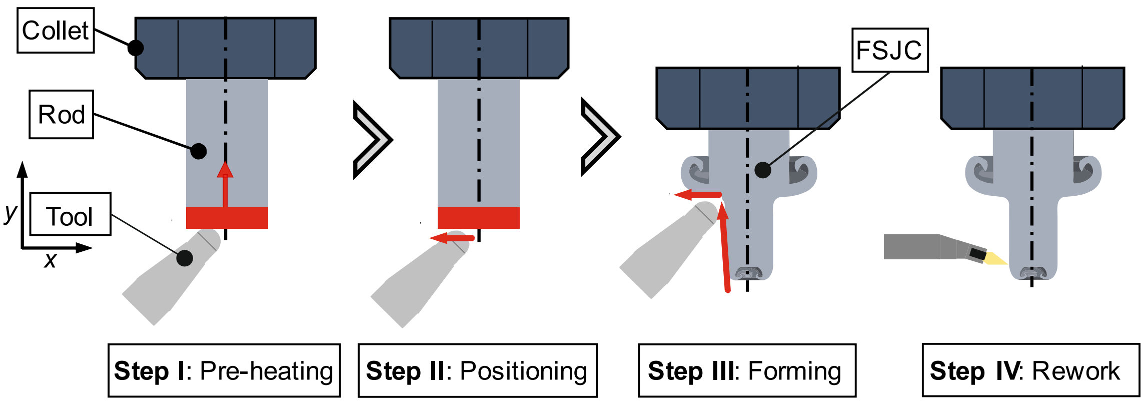

Figure 1: Principle of the first process stage to produce FSJC.

Process stage 2. Joining process. In the second process stage, the FSJC are used to join two sheets of different types (length in each case $l = 105$ mm and $b = 45$ mm). The sheets overlap by $\Delta l = 16$ mm and the joining point is placed centrally. In contrast to the sheet made of the aluminium casting alloy EN AC-AlSi9, the steel sheet of the alloy HCT590X has a pre-hole ($d = 6$ mm). In the joining process presented in this publication, the FSJC-side cast aluminium plate, which has no pre-hole (analogous to flow drilling), is driven-through (see Fig. 2). The FSJC produced in the previous process stage from the round bar of the steel material C45e has a significantly higher mechanical as well as temperature strength compared to the aluminium cast plate. This allows the aluminium cast plate to be driven-through, thus avoiding the insertion of a pre-hole. During the drive-through of the aluminium cast plate with the FSJC, heat is generated, which in this case is used to reduce the flow stress of the aluminium cast plate and thus to reduce the process forces as well as the tool loads. The FSJC heated by the drive-through is further fed in the negative y-direction, so that a frictional contact with the bottom of the die subsequently occurs, which leads to a further strong generation of frictional heat. The material volume of the FSJC, which is also reduced in strength due to this frictional contact, now flows laterally and completely fills the die, forming the interlock required for the high strength of the joint. After reaching the end position, both the feed and the rotational speed are stopped and the joint is removed.

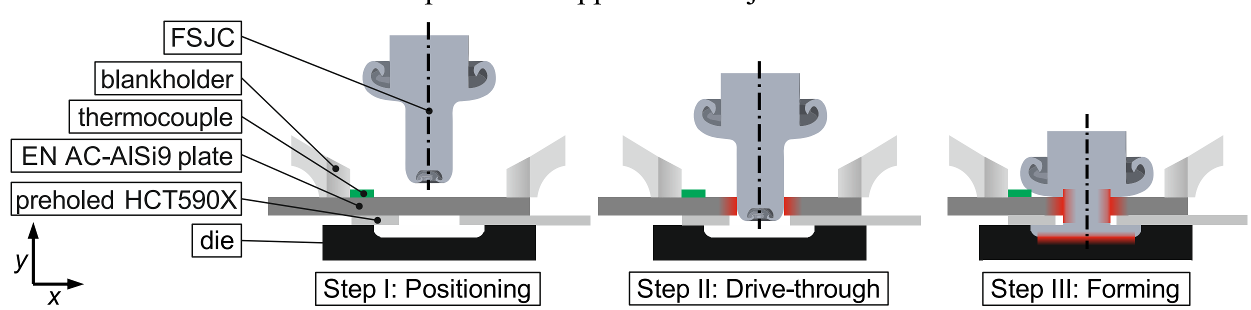

Figure 2: Principle of the second process stage, the joining of two sheets.

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Materials, methods and processes

Central influencing variables of the joining and driving through process are the rotational speed as well as the feed of the auxiliary joining element [13], which have been varied in this paper in a wide interval in a two-stage test plan for the second process step of driving through (low/high). Four repetitions are carried out for each parameter combination. For the joining process itself, constant parameters of the rotational speed of n = 10,000 rpm and feed f = 30 mm/min are used. With regard to the relative movement that occurs between the rotating and fed auxiliary joining element and the stationary sheets, the rotational speed as well as the feed can be combined in one parameter, the related feed (feed per rotational speed). To investigate whether the rotational speed or feed as adjustable variables or the resulting dependent relative movement of the related feed is the main influencing variable on the driving through, the first as well as the fourth test series have an identical related feed of r_f = 0.015 mm/rev (Table 1).

Table 1: Experiment plan with resulting, related feed.

Test series	1	2	3	4
Rotational speed n [rpm]	2000	2000	10000	10000
Feed f [mm/min]	30	150	30	150
Related feed r_f [mm/rev]	0.015	0.075	0.003	0.015

To characterize the temperature and force as well as the properties of the joined component, different measuring and testing methods are used, which are described in the following. The forces occurring during the joining process (second process stage) are recorded by means of a strain gauging load cell (K6D175 50kN/5kNm/UP13) from ME-Meßsysteme GmbH Hennigsdorf, Germany, and subsequently processed with a measuring amplifier from Hottinger Brüel & Kjaer GmbH in Darmstadt, Germany (QuantumX Module MX440B). Due to the surface properties of the aluminium, a non-contact temperature measurement using a thermographic camera is here not possible. However, to record the different heat generation of the drive-through and the forming (depending on the rotational speed used and the feed rate), a type K thermocouple (G/G-24-KK-IEC) from Therma Thermofühler GmbH in Lindlar, Germany, is used at a distance of Δl = 20 mm from the joint. The measurement signal is also processed using the measurement amplifier characterized above. The previously characterised tooling system in combination with the position and alignment of the sheets is used to directly produce shear tensile specimens. These joints are then tested in accordance with the standard DVS/EFB-3480-1: Testing of Properties of mechanical and hybrid (mechanical/bonded) joints, which applies to the testing of steel and non-ferrous metals up to a thickness of $t \leq 4.5$ mm. In the course of the light microscopic (LM) examinations as well as the EBSD analyse, the joined samples were embedded in the embedding agent CEM1000 blue (Cloeren Technology) and then ground with a grain size of up to 4000. Subsequently, the specimens were polished for 24 h by an automatic polishing machine using the polishing suspension Silica suspension (Cloeren Technology) which includes nano particles with a size of 50 nm. Die LM images are taken by using the Keyence VHX5000 digital microscope. In addition, EBSD images are taken using the Zeiss Ultra Plus scanning electron microscope (SEM) to investigate the microstructure. For this application, a magnification of 500 is used at a working distance of 13.5 mm and a step size of 0.15.

The investigations involved the manufacture of cast plates consisting of the aluminium casting alloy AlSi9 using the sand casting process. For this purpose, quartz sand with an average grain size of 260 µm was used in combination with the cold-curing resin-hardener mixture Pentex L and the zircon coating 3139 KBV from Hüttenes Albertus. It was applied with a thickness of 250 µm and serves to prevent melt penetration into the moulding material. The quartz sand was mixed with the resin hardener mixture at a ratio of 100 : 0.6. Casting plates with a thickness of 2 mm and basic dimensions of 240 x 120 mm are produced.

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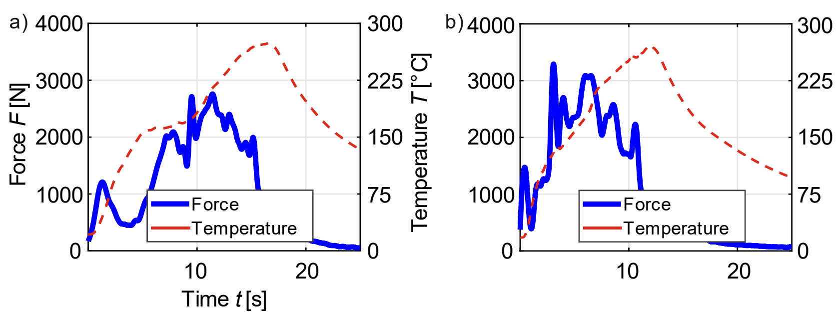
Characteristic mechanical properties such as tensile strength, elongation at fracture and Brinell hardness of AlSi9 cast plates with a thickness of 2 mm can be taken from the previous study by Neuser et. al [15].

Characteristics and properties of the joining process

In this subchapter, the properties, and characteristics of the partial-pre-hole-free joining process are explained and the influence of processing the casting alloy as well as the influence of the different variables are described. First of all, an exemplary and characteristic force and temperature curve determined for partial-pre-hole-free joining is presented in Fig 3. and described for two different feed rates during driving through (in a) f = 30 mm/min, in b) f = 150 mm/min). In the overall evaluation, the results of four examinations for each parameter combination are considered. The figure shows that at the time t = 0 s a direct contact of the auxiliary joining element with the pre-hole-free cast plate occurs. For the low feed rate of f = 30 mm/min, a minor force increase followed by a force decrease can be determined in comparison to the high feed rate. The reason for the decrease in the force following the setting of the local maximum is the softening of the cast plate that occurs due to the frictional heat inserted. In the third process step (the forming of the closing head), a strong increase in the process force can initially be determined due to the significantly increased friction surfaces in the die with a diameter of d = 14 mm. After reaching the global maximum force in relation to the entire process, the process forces also decrease significantly here due to the softening of the auxiliary joining element made of C45e material.



Sheet materials
EN AC-AlSi9, t = 2 mm
HCT590X, t = 1 mm
Joining element
C45e, d = 5.5 mm, l = 8 mm
Die geometry
Flat die, d = 14 mm, t = 1.5 mm

Figure 3: Variation of the process force and temperature during the driving through and forming of the closing head with a) n = 2000 rpm, f = 30 mm/min and b) n = 2000 rpm, f = 150 mm/min.

Besides the influence on the process force, a direct influence of the feed rate on the temporal course of the heat input can be shown. For the low feed rate of f = 30 mm/min, a constant temperature level in the range of $T \approx$ 155 °C is established (for a short time) following the driving through of the cast plate. For the feed rate of f = 150 mm/min, an almost constant increase in temperature up to the maximum can be determined. An influence of the feed rate on the temperature maximum cannot be determined when considering the points of investigation presented here.

To illustrate the influence of the variation of the rotational speed and the feed (representable as the variation of the related feed) and to assess the robustness or repeatability of the process in the form of the setting of constant characteristic values of the force as well as temperature measurement, the results of the test points are compared in the following. No significant correlation can be determined between the rotational speed or the feed rate and the measured maximum temperatures. The reason for the insignificant correlation is the strong fluctuations of the maximum temperatures over a test series with constant rotational speed and feed. For example, the standard deviation SD = 44 °C of the test series with a rotational speed of n = 10,000 rpm and a feed rate f = 30 mm/min at an average maximum temperature of T_{max} = 259 °C, which corresponds to a percentage deviation of approx. 17 %. Although the results vary, a technological explanation can be seen in the deviations within the geometry of the auxiliary joining elements, which are due to the wear of the sintered carbide tools. Despite the targeted, machining reduction of the shaft diameter to a uniform diameter, the edge radius as well as the diameter of the flange show deviations within a test series.

For the evaluation of the energy required to produce the joined joint, the measured process forces are considered. On the one hand, the maximum force during the joining process and, on the other hand, the average force during the forming of the closing head (process phase with the highest mechanical loads) are considered. For all investigation points, the maximum forces occurring during the process significantly exceed the average forces present during the forming of the closure head. In addition, it can be determined that, analogous to the observation of the temperatures, strong (standard) deviations also occur for the process forces within the individual test series with identical feed rates and rotational speeds. Nevertheless, the statistically non-significant tendency of increasing forces (maximum as well as average force) with increasing feed can be determined.

Characteristics of the joining connection

The mechanical testing of the joined tensile specimens shows that a high and suitable strength could be achieved for all specimens regardless of the process parameters used. The maximum forces in the shear tensile test before failure of the joints are between $F_{max} = 3.3$ kN and $F_{max} = 5.2$ kN. For all joints, it applies that due to the lower strength of the cast plate compared to the steel sheet, this cast plate breaks out and the joint fails at this point. Analogous to the results described above with regard to the process forces and temperatures during joining, the determined maximum forces of the joint also show no significant influence of the process parameters of the feed and the rotational speed.

In the scope of the investigations, LM images of the AlSi9 and HCT590X plates joined using frictional forces were obtained. An example of such an image is shown in Fig. 4. Here, the arrangement is as follows: on the die side, the steel sheet HCT590X is presented, and on the punch side, the AlSi9 cast plate is given. In the forming area of the AlSi9 cast plate, it can be seen that the dendritic microstructure in the die-side edge area (1) has formed a very fine Si eutectic as a result of partial remelting, as well as the dendritic α-aluminum has been formed by the joining process and has assumed a stem-like morphology. Just the latter can be seen in the LM image (2). During the joining process, no cracks were initiated in the cast plate, as is common, when using conventional mechanical joining processes. This can be avoided by modify the microstructure [15].

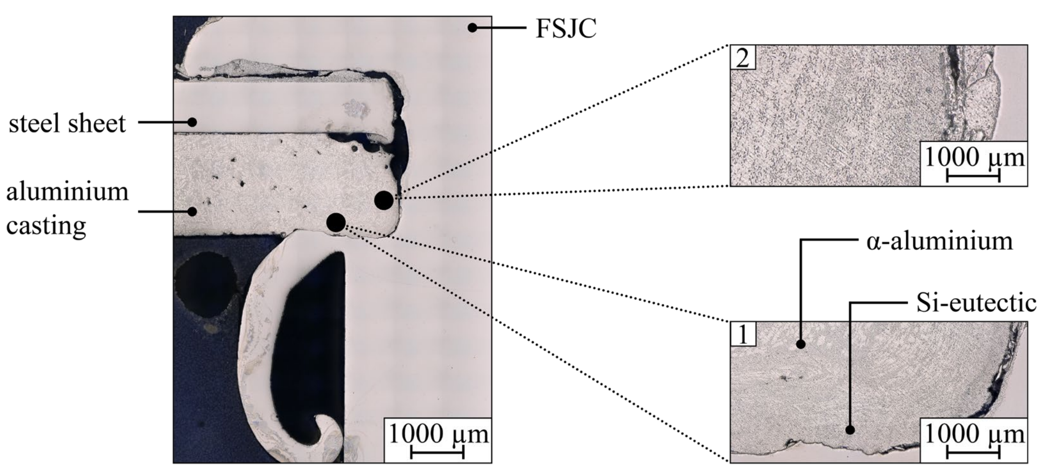


Figure 4: Cross–section LM image of joint using FSJC.

To illustrate the forming process on the joint, Fig. 5 shows examples of EBSD images of the forming zone and a comparison with the as-cast condition. In addition, the EBSD images of the

FSJC in the same conditions are shown. Due to the forming process as well as the partial melting, grain refinement can be observed in AlSi9. In the basic material (AlSi9), large grains are evident, which is typical for a sand-cast microstructure. Due to the low plate thickness of 2 mm, a solidification-related orientation of the grains is detectable. In comparison, in the heat-affected zone, a finer microstructure and, due to the forming process, an orientation alteration of the grains can be observed. In the case of the rivet material C45e, recrystallization takes place as a result of the previous forming and the thermal influence. The comparison of the two EBSD images shows the significantly smaller grains.

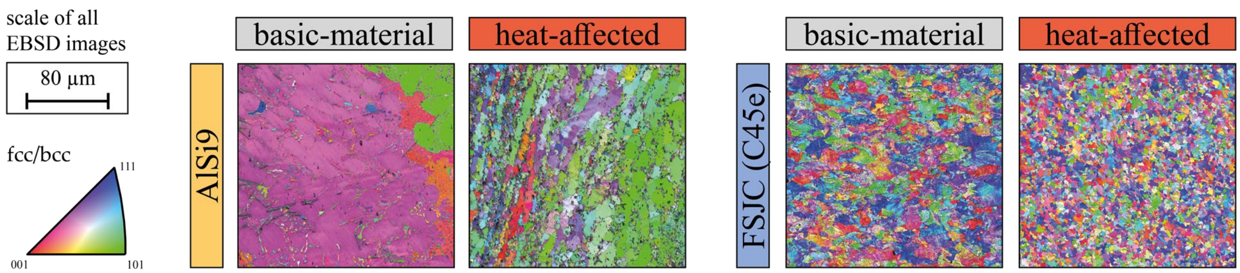


Figure 5: EBSD-analyse of aluminium casting (left); FSJC rivet consisting of C45e (right). In addition, a difference is made between images taken on the basic material and in the heat-affected zone.

Conclusion

The results of this study show that, regardless of the parameters used for the thermomechanical joining process, suitable strengths can be achieved for the joint between the hypoeutectic aluminium casting alloy plate and the steel sheet for all the joints investigated. The combination of joining processes and hypoeutectic aluminium casting plates used here can therefore overcome the challenges described in the prior state of the art with regard to joining aluminium casting alloys. An influence of the process parameters of the rotational speed and the feed rate on the force and temperature curves in the different process phases could be demonstrated. Due to the friction-induced application of heat and the associated partial melting, a grain refinement in the AlSi9 aluminium alloy due to recrystallisation can be determined. Furthermore, no cracks in the cast material can be detected at the joint, as is the case with conventional mechanical joining processes.

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