Joining suitability of cast aluminium for self-piercing riveting

M Neuser1*, F Kappe2, M Busch1, O Grydin1, M Bobbert2, M Schaper1, G Meschut2 and T Hausotte3

1 Department of Materials Science, Paderborn University, Paderborn, Germany
2 Laboratory for material and joining technology, Paderborn University, Paderborn, Germany
3 Institute of Manufacturing Metrology, Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU), Nürnberg, Germany

*Corresponding author: neuser@lwk.upb.de

Abstract. Due to the increasing importance of reducing CO2 emissions, lightweight construction strategies are highly emphasized in the automotive industry. One of these strategies is lightweight moulding, which is used, for example, in the space frame design. Here, lightweight materials are joined with castings to form a structure that is well adapted to the application of force. Especially for multi-material joints, self-piercing riveting is frequently used as joining technology due to the wide range of joining possibilities and the high load-bearing capacities. However, the susceptibility of cast aluminium alloys to cracking due to the brittle microstructure causes great challenges for mechanical joining by self-piercing riveting. Therefore, this study investigates the suitability of the cast aluminium alloy AlSi9Mn for self-piercing riveting. Various improvement strategies are utilized to increase suitability considering of joining as well as material parameters. An evaluation of the joint and its damage characteristics is provided by metallographic analysis and industrial X-ray computed tomography (XCT). Metallographic analysis is used to determine the quality relevant characteristics of the joint, while XCT provides volumetric and non-destructive testing of the joint for internal cracks.

1. Introduction
The increasing demand for mobility of both goods and people is facing the limitation of natural resources and far-reaching changes in climate policy to reduce CO2 emissions. In addition to the development of new drive concepts, these new economic and ecological requirements are also leading to the consistent use of lightweight designs in car bodies. However, due to metallurgical incompatibilities and in view of the focus on process robustness, the use of these different materials leads to conventional thermal joining technologies are reaching their limits and mechanical joining technologies are increasingly being used. With regard the lightweight mould construction, cast components allow the possibility of well adapting the structure to the application of force. The mechanical joinability of these components depends on their ductility, which is influenced by the microstructure. Since high-strength cast aluminium alloys have relatively low ductility, it is often not possible to produce a crack-free joint in mechanical joining processes. This paper deals with the suitability of joining aluminium castings and the study of various improvement strategies on the joint formation.
2. State of the art
The state of the art covers three topics. First, the casting technology and material fundamentals are discussed, in this case the sand casting process and the aluminium-silicon casting alloy used. The second focus is on the technical joining description of self-piercing riveting. Lastly, industrial computed tomography is discussed, which is used for non-destructive testing of the joints.

2.1. Aluminium Casting Alloys
The realisation of multi-material design in modern automotive engineering requires the joining of sheet metal or extruded profiles with cast components made of different materials [1]. Due to the desired weight reduction, these cast components usually consist of age-hardenable aluminium alloys of the Al-Si(Mg) group, which can only be welded to a limited extent [2]. Ductile Al-Si alloys are particularly advantageous for such applications, as they are easier to join. Structural components made of the Al-Si alloy are mostly manufactured using the die-casting process [1].

Aluminium casting alloys are divided into hypoeutectic, eutectic and hypereutectic alloys. The eutectic point for the Al-Si system is at 12.5 % Si. The mechanical properties of cast aluminium alloys vary depending on composition and heat treatment [1]. The binary Al-Si system is characterised by castability, corrosion resistance and fluidity, a disadvantage being its somewhat lower strength in comparison. It is possible to influence the strength, ductility and castability of hypoeutectic alloys by modifying the eutectic, which can be done both by the sand casting process and by the addition of sodium or strontium [3]. However, other factors such as solidification rate, microstructure and the respective casting process also have a major impact on the mechanical properties [4]. Strontium is used to refine the cast structure of aluminium-silicon casting alloys [5]. Refining can transform the coarse and partially lamellar eutectic into a finely dispersed phase, and it also increases tensile strength as well as elongation at fracture. Silicon solidifies in the crystallographic <112> plane. In this process, the silicon atoms arrange themselves in steps across the solidus-liquidus interface, forming simple twins. Since the solidification proceeds linearly, it leads to a flat and unbranched solidification morphology of the silicon. Refining elements such as sodium or strontium increases the number of twins to be formed, which in turn serve as nucleation points for the solidifying silicon atoms. The refining elements result in a fine and branched silicon network [6].

2.2. Sand casting
In sand casting, a distinction is made between lost mould casting and permanent pattern casting. Although there are also processes in which a lost pattern is used, these will not be considered further here. The sand casting process allows the casting of all aluminium alloys, which also includes alloys that are prone to hot shortness [4]. Green sand or dry sand is used as the moulding material, the latter requiring a binder system to create a solid mould. The moulding material serves not only to provide a solid mould for the casting material that can withstand the high casting temperatures without damage, but also to prevent pores in the subsequent casting thanks to its high permeability to air and casting gases. The sand casting process allows a component thickness of 4 mm, although wall thicknesses with a minimum of 2 mm can also be cast. Compared to other casting processes, the strength is lower due to the lower solidification speed. It is possible to improve the mechanical properties through the choice of sand, as the heat capacity can be increased, which in turn increases the solidification rate [3].

The process for sand casting is the same regardless of whether green sand or dry sand is used. The casting pattern and the sprue system pattern are placed in so-called mould boxes, which are usually made of metal or wood. Then, the casting box is filled with the moulding material and compacted by hand or with a pneumatic tamper. Finally, the models are removed, and the resulting carvings can be cast [7].

2.3. Self-piercing riveting
Self-piercing riveting (SPR) mentioned in DIN 8593-5 is of particular interest for joining of two or more materials with auxiliary joining element due to the reduction of thermal input. The SPR process can by divided into four stages (see Figure 1). First, the blank holder, which encloses the rivet, fixes the sheets
on the die. Then the punch presses the rivet into the punch-sided sheet, initiating a cutting phase. The rivet penetrates the punch-sided sheet and the resulting slug is stored in the shank of the rivet. Now, the rivet undergoes plastic deformation and expands radially into the die-sided sheet, resulting in the formation of an interlock. By upsetting of the rivet, a force-fit and form-fit connection is created. Finally, the punch and the blankholder reset to their initial position. The quality of a SPR joint can be determined based on various quality-relevant characteristics. Among the most important parameters (see Figure 1, c) are the interlock (f), the minimum die-side material thickness (t_r) and the rivet head position (p_h) [8].

Figure 1: a) Tooling for SPR, b) Process sequence for self-piercing riveting and exemplary joining force-displacement curve, c) Quality-relevant characteristics of a SPR-joint [8].

Due to the material properties of cast aluminium, cracks can occur within the joining process using SPR-technology. These cracks can reduce the corrosion resistance of the joint, depending on the application. In addition, the joint strength of materials with low ductility can be negatively affected by the cracks, although this effect can be considered minor, if the cracks are mainly superficial [9]. To improve the cracking behaviour during joint formation, dies with a ring groove can be used. Hereby, the formation of the interlock can be improved and the load on the rivet can be reduced [10]. Zhao et al. [11] have shown in their study that additional heat treatment of casting material before joining can reduce crack initiation. However, despite the improved joint formation, a continuous decrease in shear strength was observed. Another possibility to increase the joining suitability of materials with limited ductility is a new die tool concept with an adjustable die bottom. This enables the superimposition of compressive stresses on the parts to be joined in order to prevent cracking [12].

2.4. X-ray computed tomography

While X-ray computed tomography is widely used in medical diagnosis, industrial X-ray computed tomography (XCT) is a relatively new technology in component diagnosis. It provides volumetric imaging for non-destructive testing. In XCT, a component is positioned in the measuring device between an X-ray tube and a detector (see Figure 2). After scanning the part with a high number of projections from different directions, a volume model can be reconstructed, allowing an analysis of the geometric features as well as cracks. Based on the sectional images and using conventional evaluation software, components can be examined for internal gaps, cracks and pores. XCT is an artefact-laden procedure [13]. These artefacts are particularly pronounced in multi-material components such as the investigated riveted joints due to their different absorption characteristics. The artefact distribution is also dependent on the orientation of the component on the manipulator of the device. If the aspect ratio of the component varies, then the orientation during measurement is always accompanied by a compromise [14].
3. Experimental details

To evaluate the mechanical properties of the components selected for joining and to interpret the results of the microstructure analysis, it is necessary to know the exact chemical composition of the examined materials. For this study, the wrought aluminium alloy EN AW-6014 in the T4 temper with a sheet thickness 2.0 mm and the aluminium alloy AlSi9Mn also with a thickness of 2 mm were investigated. The chemical compositions of the materials EN AW-6014 and AlSi9Mn, which were determined using an optical emission spectrooscope of the company Bruker model Q4 TASMAN, are shown in Table 1.

The AlSi9Mn alloy was selected for this study because it exhibits high ductility in the as-cast condition, which is required in joining processes. Furthermore, it is possible to increase the ductility of this alloy by a specific heat treatment in order to avoid the formation of cracks in the closing head of a self-piercing riveting joint. The strength and the ductility of the Al-Si alloys are influenced by the characteristics of the Si structure. If the silicon crystal structure in the eutectic is minimised by refinement, the mechanical properties also increase [4]. Permanent refinement with strontium causes a finer formation of the eutectic and leads to an increase in ductility [3]. Particularly important is the strontium content of the aluminium alloy AlSi9Mn of 0.048 %.

Table 1: Chemical composition of the wrought aluminium alloy EN AW-6014 and the casting aluminium alloy AlSi9Mn determined by means of an optical emission spectrometer.

| Elements | Al    | Mg    | Si    | Fe    | Cu    | V    |
|----------|-------|-------|-------|-------|-------|------|
| Mean value in weight-% | 98.210 | 0.693 | 0.520 | 0.220 | 0.135 | 0.053 |
| Standard deviation | 0.026 | 0.0050 | 0.0095 | 0.0095 | 0.0015 | 0.0001 |

| Elements | Al | Si | Mn | Mg | Fe | Sr |
|----------|----|----|----|----|----|----|
| Mean value in weight-% | 89.31 | 9.746 | 0.451 | 0.017 | 0.110 | 0.048 |
| Standard deviation | 0.080 | 0.060 | 0.0043 | 0.0005 | 0.011 | 0.0002 |

In addition to the chemical composition of the materials, the mechanical properties of the cast aluminium alloy as well as the wrought aluminium alloy were also determined experimentally by means of quasistatic tensile test according to DIN 50125 and DIN EN ISO 6892-1 by using a tensile testing machine from the company MTS model 858 Table Top. They are shown in Table 2. Brinell hardness testing was conducted using a Franke Frankoskop and according to DIN EN ISO 6506-1. The properties of the AlSi9Mn were tested on specimens produced by the sand casting process. The melting process
was carried out in a resistance furnace, where the melt was superheated to a temperature of 720 °C. The melt was treated with Degasal T 200 before being poured into the green sand mould. In order to investigate the joining suitability of cast aluminium, samples were joined using a TOX® TE-X system. To analyse the joining point quality, in addition to macrosections and XCT examinations, shear tensile tests are carried out. The wrought aluminium alloy AW-6014 was used on the punch side and the casting as die-sided material. The joined shear tensile specimens (see Figure 6) had a free clamping length of 95 mm (lf), an overlap of 16 mm (lü) and a width of 45 mm (b). The shear tensile tests were performed on a Zwick Z100 tensile-compression testing machine, using a test velocity of 10 mm/min.

Table 2: Mechanical properties of the wrought aluminium alloy EN AW-6014 [15] and the cast aluminium alloy AlSi9Mn tested on 2 mm thick tensile specimens.

| Material          | Rm in MPa | Rp0.2 in MPa | Hardness in HBW 2.5/62.5 | A in % |
|-------------------|-----------|--------------|--------------------------|--------|
| EN AW-6014, T4    | 232       | 127          | 73                       | 22     |
| AlSi9Mn           | 197       | 92           | 63                       | 10     |

4. Results and Discussion

When using self-piercing riveting as joining technology, selecting the most suitable rivet-die combination is crucial for the formation of the joint. In particular, the rivet length and the die depth have a significant influence on the resulting minimum die-side material thickness and the formation of the interlock. Although a large die depth encourages interlock formation [16], it can however contribute to cracking of the closing head if aluminium casting is used (configuration A). A lower die depth can significantly reduce the risk of cracking of the closing head, as shown in Figure 3 (configuration B), and at the same time maintain the quality-relevant characteristics at almost the same level.

Figure 3: Improving joining suitability by an adapted die selection; a) Macro section of configuration A, b) Cross section through the XCT built volume model of configuration A, c) Macro section of configuration B, d) Cross section through the reconstructed volume of configuration B.

As Figures 3 b) and d) show, the two joining partners made of aluminium absorb less X-radiation than the rivet, which is made of steel. Nevertheless, both the joining partners and the rivet can be visualised well by XCT. In the sectional images, cracks are countable by visual inspection and a selection of artefacts can be determined by experience. Detected cracks in the closing head are highlighted by white arrows. In both figures, metal artefacts, shown by grey arrows, as described in [17].
indicating a crack in the component. The reconstructed volume of configuration A has 10 cracks on the edge bent by the die. In some cases, the crack depth reaches the rivet. An opposite displacement of the crack flanks in the crack propagation direction, as shown, is usually caused by a shear load [18]. A joint with such deep cracks is in a real process considered to be unacceptable. By reducing the die depth, the number of detectable cracks on the die side could be minimized to a single one, which was also only superficial. Whether the weakening of the surface results from an existing pore in the casting material cannot be assessed in retrospect. One reason for crack initiation is the lower plastic deformation of the cast aluminium compared to the wrought aluminium alloy.

4.1. Further improving joining suitability

In order to improve the joining suitability of aluminium alloys with aluminium cast, two strategies are pursued. The first improvement strategy aims to increase the joining speed. Increasing the joining speed can influence the geometric formation of the joint. In addition, it can reduce the sheet metal damage caused by the deformation of the parts when joining at normal speed due to large tensile strain. This may have a positive effect on joint strength [19]. Due to the increased joining speed, the required cycle time can be significantly reduced, which makes the joining process more efficient. To investigate the influence of the joining speed (configuration C), a C rivet 5.3x5.5 H4 was again used in combination with the FM 100 2012 die. The joining speed was increased from 20 mm/s to 120 mm/s. An examination of the joint in macrosection showed that the higher speed had no significant influence on the quality-relevant parameters. The minimum die-side material thickness and the rivet head position remained similar, while the interlock was slightly increased. However, the higher joining speed increased the number of detectable cracks in the closing head (see Figure 5, c), which can be seen in the reconstructed volume of the CT measurement. Since these were only superficial or close to the surface, a negative influence on the load-bearing capacity is not be expected.

One challenge is the high silicon content of the cast aluminium alloy, because it reduces the elongation at fracture, which is important given the large deformation at the rivet foot [11]. Figure 3 shows that crack initiation starts at the foot of the rivet, due to the high deformations. The cracks cannot only be explained by the lower elongation at break. The observation of Zhao et al. [11] shows that the eutectic silicon is the crack initiator due to the deformation induced in the joining process. This is attributed to the brittleness of the eutectic phase, which reduces the elongation at fracture of the cast material [4]. One way to modify the eutectic silicon is to alloy it with strontium, as explained in Chapter 3. This leads to an increase in elongation at fracture [20]. Since the aluminium casting alloy used here was already long-term refined with strontium, it was improved from the outset, but a further strategy was required.

Therefore, heat treatment of the previously cast component is the second strategy in this study to increase the joinability of an aluminium casting alloy. The study by Jarco et al. [21] showed that the hardness of an AlSi11 alloy can best be reduced by heat treatment at 380 °C between 4 and 9 hours, down to a hardness value of < 52 HBW is achieved [21]. Due to the similar silicon content of our cast aluminium alloy (9.7 %) and the AlSi11 alloy used by Jarco et al. (10.9 %), the same starting temperature (380 °C) for heat treatment was selected for this study. The study by Jarco et al. [21] also showed that the hardness is hardly reduced above a holding time of 4 hours. To reproduce a process that is as economical as possible, the specimens were held for 4 hours. The heat treatment resulted in the desired reduction in hardness. Compared to the measured Brinell hardness in the as-cast state of 63 HBW (see Table 2), a hardness of 50 HBW could be achieved after the heat treatment. Figure 4 shows two light optical microscopy (LOM) images, a) the as-cast condition, b) the condition after heat treatment. In a) it can be seen that the eutectic has already been modified by strontium addition to such an extent that the otherwise needle- and plate-shaped eutectic silicon is no longer completely sharp. In comparison, it is evident in LOM image b) that the eutectic microstructure is even finer made after the heat treatment, and the eutectic silicon needles have become even more spherical. However, as Figure 5 shows, no cracks appear in the closing head when using the same rivet-die combination. Holding at a temperature of 380 °C for a long time causes the aluminium to be excited at the contact surfaces to the
eutectic silicon. This causes the silicon to form rounder between the α-aluminium and increasingly lose its needle-like structure. This can also be seen in the study by Haque et al. [22]. The finer and rounder formed silicon improves the ductility of the cast material [23].

![Figure 4: LOM image of the castings of the aluminium alloy AlSi9Mn: a) As-cast, b) After heat treatment.](image1)

After the heat treatment configuration D, the interlock, minimum die-side material thickness and rivet head position remained similar. In addition, the residual stresses in the eutectic silicon are minimised, resulting in fewer microcracks. This affected the joining process in the sense that fewer or no cracks were visible in the closing head of the joint (see Figure 5, d).

![Figure 5: Image of closing head of a) Configuration A (C 5.3x5.5 H4, FM 100 2018, joining speed 20 mm/s, not heat-treated), b) Configuration B (C 5.3x5.5 H4, FM 100 2012, joining speed 20 mm/s, not heat-treated), c) Configuration C (C 5.3x5.5 H4, FM 100 2012, joining speed 120 mm/s, not heat-treated), d) Configuration D (C 5.3x5.5 H4, FM 100 2012, joining speed 20 mm/s, heat-treated).](image2)

4.2. Investigation of joint load-bearing capacities
The improvement strategies outlined in the previous chapter showed that a reduction in the formation of cracks in the closing head is influenced in particular by correct die selection. Furthermore, the joint formation can be improved by an increased joining speed, which at the same time leads to a lower cycle time, as well as by an additional heat treatment to homogenize the cast aluminium microstructure. In order to further investigate the influences of the modified closing head formation, the joint load-bearing capacities (see Figure 6) were determined in accordance with DVS/EFB Guideline 3480-1. The diagram shows in normalised form the maximum force \( F_{\text{max}} \), the displacement when reaching the maximum force \( s_{F_{\text{max}}} \) and the energy absorbed upon 70 % force reduction \( W_{0.7F_{\text{max}}} \).
Basically, the evaluation of the shear tensile tests shows that higher maximum forces and deformation energies can be absorbed by improving the formation of the closing head. However, the displacement on reaching the maximum force remains at a constant level. Only in configuration D the maximum force is reached at a higher displacement. The sample thus absorbs more energy through plastic deformation before the maximum force is reached. However, the maximum force achieved was lower than with configurations B and C, despite using the same rivet-die. The normalized representation of the shear tensile strengths also showed that additional heat treatment of the cast aluminium specimens improves their ability to absorb deformation energy. One reason for this is the eutectic silicon modified by the heat treatment, which, as described in Chapter 4.1., is much less of a crack initiator due to the rounder eutectic than when the casting is not heat-treated. The elongation at break becomes greater and larger deformations can be carried out, especially at the rivet foot, without microcracks forming on the sharp-edged silicon plates. The comparison of configurations B and C shows that the higher joining speed has a positive influence on the load-bearing capacity of the joint, which can be explained by the slightly increased interlock formation, as this is largely responsible for the load-bearing capacity of the joint. Furthermore, as already assumed in the previous chapter, superficial cracks have no effect on the joint strength.

5. Conclusion
In this study the joining suitability of cast aluminium by using self-piercing riveting was investigated. Therefor the material properties were examined. Using different tool configurations, the influence of the die geometry on the joint formation could be investigated. The joining suitability was analysed using macrosections, XCT scans and shear tensile tests. By using a flat die, the number of cracks occurring in the closing head could be significantly reduced. Furthermore, increased joining speed in order to increase the efficiency of the joining process was investigated. Although the number of cracks in the closing head was increased using a higher joining speed, no negative influence on the load-bearing capacity of the joint was observed, as the cracks were superficial or near to the surface. The load-bearing capacity could even be slightly increased by modifying the geometrical formation of the joint. An additional heat treatment of the cast component before the joining process completely prevented the formation of cracks in the closing head. However, this also changes the load-bearing behaviour of the joint. In particular, as a result of the changed microstructure, the energy absorption was improved whereby the maximum transmittable force was reduced. Further investigations will aim at the extent to which these results can be transferred to cast components produced in the gravity die casting and
twin-roll casting. Particularly due to the different solidification rate compared with sand casting, a different cast structure is expected, which in turn influenced the joining properties.

**Acknowledgment**

Funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) – TRR 285 – Project-ID 418701707. The authors thank the DFG for their organisational and financial support.

**References**

[1] Mallick P K 2011 *Materials, design and manufacturing for lightweight vehicles (Woodhead Publishing in materials)* (Boca Raton, Fla, Oxford: CRC Press)

[2] Machuta J, Nová I and Kejzlar P 2017 *Manufacturing Technology* 17 772–7

[3] Kaufman J G and Rooy E L 2004 *Aluminum alloy castings: Properties, processes, and applications* (Materials Park, OH: ASM International)

[4] Lumley R N 2018 *Fundamentals of aluminium metallurgy: Production, processing and applications* (Woodhead Publishing series in metals and surface engineering) (Cambridge, MA: Woodhead Publishing)

[5] Hatch J E 1984 *Aluminum: Properties and physical metallurgy* (Metals Park, OH: American Society for Metals)

[6] Gruzleski J E and Closset B M 1999 *The treatment of liquid aluminium-silicon alloys* (Des Plaines, Ill.: American Foundrymen's Society, Inc)

[7] Fredriksen H and Åkerlind U 2010 *Materials processing during casting* (Chichester, England, Hoboken, NJ: Wiley)

[8] DVS/EFB 2018 Merkblatt Stanznieten -Überblick- (3410) (DVS Media GmbH)

[9] Jäckel M, Coppieters S, Hofmann M, Vandermeiren N, Landgrebe D, Debruyne D, Wallmersberger T and Faes K 110009

[10] Böllhoff Group *RIVSET® Self-pierce riveting technology: Joining of Aluminium Cast with New Ring Groove Die* https://www.boellhoff.com/de-en/news/news/2017/rivset-ring-groove-die.php

[11] Zhao X, Meng D, Zhang J and Han Q 2020 *Int J Adv Manuf Technol* 109 2409–19

[12] Drossel W G and Jäckel M 2014 *KEM* 611-612 1452–9

[13] Deutsches Institut für Normung Non-destructive testing – Radiation methods for computed tomography – Part 3: Operation and interpretation (ISO 15708-3:2017) (DIN EN ISO 15708-3:2019-09)

[14] Deutsches Institut für Normung Non destructive testing – Radiation methods for computed tomography – Part 2: Principles, equipment and samples (ISO 15708-2:2017) (DIN EN ISO 15708-2:2019-09)

[15] Böhneke M, Bielak C R and Bobbert, M., Gerson, M. 2021 *Materials Testing* 2021 [in press]

[16] Jäckel M, Falk T and Landgrebe D 2016 *Procedia CIRP* 44 293–7

[17] Carmignato S, Dewulf W and Leach R (eds) 2018 *Industrial x-ray computed tomography* (Cham: Springer)

[18] Bürgel R, Richard H A and Riener A 2014 *Werkstoffmechanik: Bauteile sicher beurteilen und Werkstoffe richtig einsetzen* 2nd edn (Wiesbaden: Springer Vieweg)

[19] O. Hahn, R. Neugebauer, G. Leuschen, C. Kraus, R. Mauermann, Hahn O, Kraus C, Leuschen G, Mauermann R and Neugebauer R 2008

[20] Glazoff M V 2019 *Casting Aluminum Alloys (Second Edition) // Casting aluminum alloys: Their physical and mechanical metallurgy* (Oxford: Butterworth-Heinemann)

[21] Jarco A 2017 *Archives of Foundry Engineering* 17 55–8

[22] Haque M and Maleque M 1998 *Journal of Materials Processing Technology* 77 122–8

[23] Zhang D, Zheng L and StJohn D 2002 *Journal of Light Metals* 2 27–36