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Overview of Current Challenges in Self-Pierce Riveting of Lightweight Materials †

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Abstract: This paper shows an overview of different analyses regarding current challenges at self-pierce riveting with solid rivets as well as semi-tubular rivets of lightweight materials like aluminum die casting, carbon fiber reinforced plastic and 7xxx series aluminum alloy. The joining process analyses will demonstrate the cause and the development as well as the influence on joint quality of individual joining process-induced defects. In addition, methods are described how these imperfections can be avoided or reduced.

Keywords: mechanical joining; lightweight materials; self-pierce riveting

1. Introduction

The importance of environment friendly mobility strengthens the need of lightweight design in the automotive industry. Due to this need, lightweight materials such as aluminum and carbon fiber reinforced plastics (CFRP) are used more and more in automotive car body constructions. According to the limited weldability, joining these materials by mechanical joining techniques such as self-pierce riveting with solid (SPR-S) or semi-tubular rivets (SRP-ST) has been established. The challenge in this regard is that these materials have limited forming capacities (e.g., aluminum die casting, CFRP) or vulnerability regarding stress corrosion cracking (e.g., 7xxx series aluminum alloy), while the joining processes locally induce large plastic deformations and tensile stresses. Consequently, self-pierce riveting of these materials can be accompanied by different joining-related imperfections that develop during the joining operation.

2. Joining Methods and Materials

In the first process step of self-pierce riveting with semi-tubular rivets, the parts and the rivet are positioned between punch, blank holder and die (Figure 1a). Next, the punch presses the semi-tubular rivet into the parts. Due to the cutting edge of the rivet, a slug is punched out of the punch-side part and is enclosed inside the rivet (Figure 1b). Following, the shape of the die causes the rivet to expand and creates an interlock (Figure 1c). At the end, the cavity of the die can be completely filled with material [1].

During self-pierce riveting with solid rivets, the rivet cuts a hole into the components to be joined and is subsequently pressed into until the countersunk set head of the rivet is installed flush with the surface of the punch-side part (Figure 1e). In the second step, the parts and the rivet are pressed by the punch and blank holder against the die at a high level of force to indent the forming ring on the die into the lower component (Figure 1f). This forms the material volume of the die-side part into the groove in the lower zone of the rivet, which then creates interlocking [1].

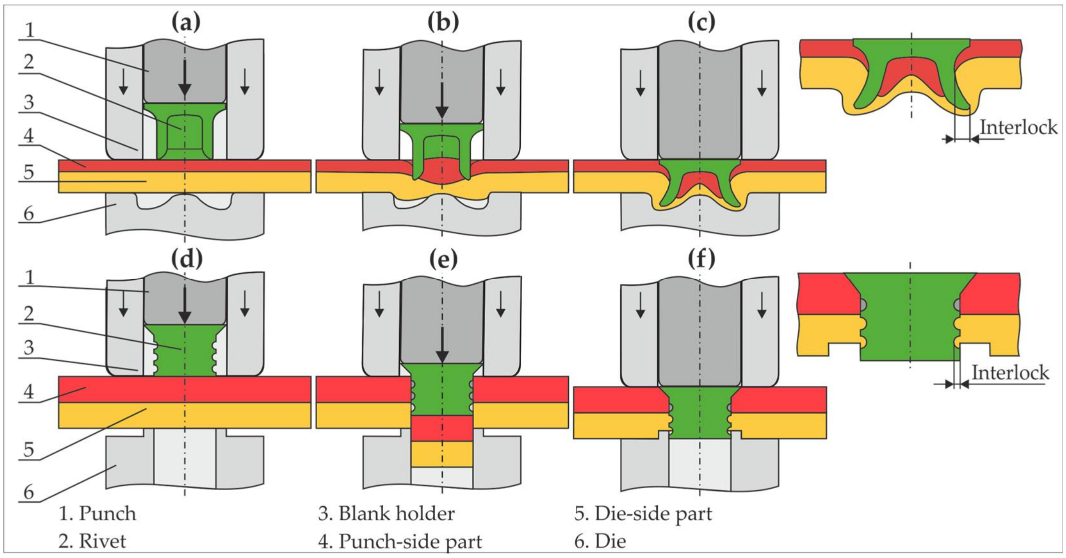

Figure 1. Principle of self-pierce riveting with semi-tubular rivets (**a**–**c**) and solid rivets (**d**–**f**) [1].

In the following sections the joining of the lightweight materials listed in Table 1 is described. These materials have very specific properties that create different challenges for mechanical joining technology.

Table 1. Mechanical properties of the investigated materials.

Type	Material		Thickness t (mm)	Tensile strength R_M (MPa)	Elongation A (%)
Aluminum sheet	EN AW-6016 T4		1.2	233	24
	EN AW-6016 T4		2.0	256	29
	EN AW-6016 T6		2.0	309	20
	EN AW-7021 T4		1.7	491	18
Aluminum die casting	AlSi9Mn F		2.0	311	9
Carbon fiber reinforced plastic	TEPEX Dynalite 201-C200	0°	2.0	785	2
		90°	2.0	725	2

3. Self-Pierce Riveting with Semi-Tubular of Aluminum Die Casting

During the self-pierce riveting with semi-tubular rivets of modern light metals like the aluminum die casting AlSi9Mn F cracking can occur, due to the relatively small elongation of the material (Table 1). The reason for the crack formation during the SPR-ST process is the occurrence of plastic deformations and tensile stresses in the parts to be joined. The risk of cracking in the aluminum die casting as well as the required interlock is strongly influenced by the die geometry or rather the depth of the die contour (Figure 2a–e). On the one hand a lower die contour depth or diameter reduces the risk of cracking in the aluminum die casting. On the other hand a deeper die contour improves the interlock formation. While, depending on the application of the joints, small cracks can have a negative effect on the corrosion resistance of the components, the influence of smaller joining process-related cracks on the joint strength can be described as very low [2].

The following approaches can be used to counteract the risk of joining process-related cracks when self-pierce riveting with semi-tubular rivets of materials with limited ductility like aluminum die casting:

- Optimization of the die geometry [3], e.g., via a numerical process development by using suitable damage models (Figure 2g–h) [2,4]
- Application of alternative rivet geometries (e.g., T-Rivet) to improve the interlock formation when using flat die geometries [5]
- Implementation of an alternative die tool concept for superimposition of the parts to be joined with compressive stresses to avoid cracking [6]

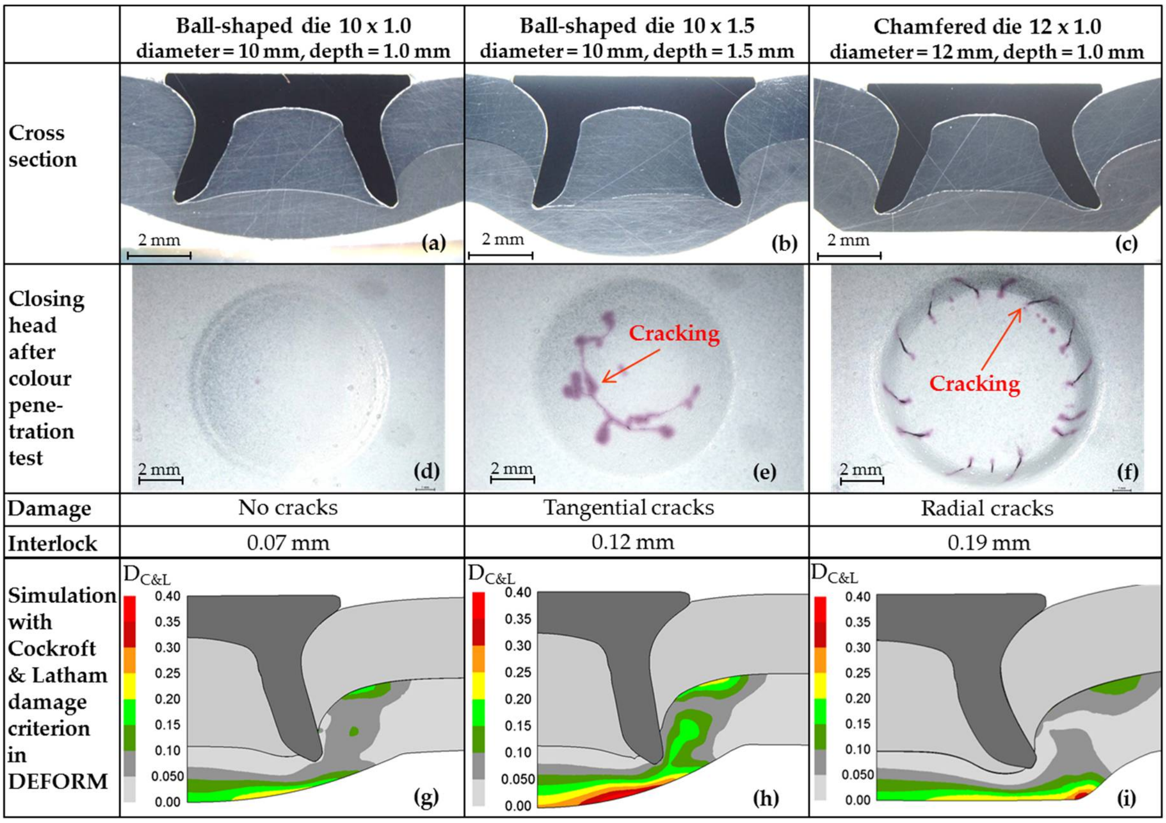

Figure 2. SPR-ST with different die geometries of EN AW-6016 T4 (t = 2.0 mm) into AlSi9Mn F (t = 2.0 mm).

4. Self-Pierce Riveting with Solid Rivets of 7xxx Series Aluminum Alloys

Especially for joining higher strength materials like 7xxx series aluminum alloys in combination with more ductile materials, self-pierce riveting with solid rivets is a suitable joining technique. In this case such as the here discussed example, the material with higher strength (EN AW-7021 T4, t = 1.7 mm) should be placed on the punch-side and the more ductile material (EN AW-6016 T4, t = 1.2 mm) should be placed on the die-side in order to favor the flow of the die-side material into the shaft grooves of the rivet to manufacture proper joints.

The challenges associated with SPR-S of high strength 7xxx series aluminum sheets mainly concern the delayed fracture in the 7xxx series aluminum sheets after the joining process. These cracks occur hours or days after the joining process between the edge of the part and the SPR-S joint. The crack starts at the part edge and progresses to the joint (Figure 3).

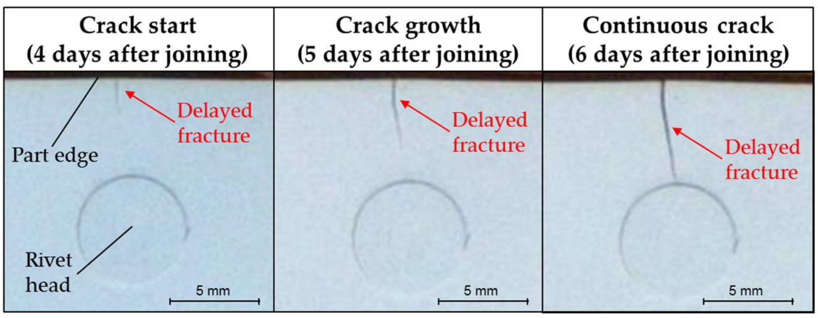

Figure 3. Delayed fracture of the EN AW 7021 T4 after SPR-S.

It is known that 7xxx series aluminum alloys are sensitive to stress corrosion cracking and the failure mode shown in Figure 3 can be associated with this corrosion form. After [7] the occurrence of stress corrosion cracking, among other things, is favored by prevailing tension-, residual- or notch stresses at cut edges. As the numerical investigations (Figure 4, left) show, through the forming of the rivet head into the punch-side aluminum sheet radial material flow is caused, which leads to tangential tension stresses when setting the rivet near to the part edge (Figure 4, right).

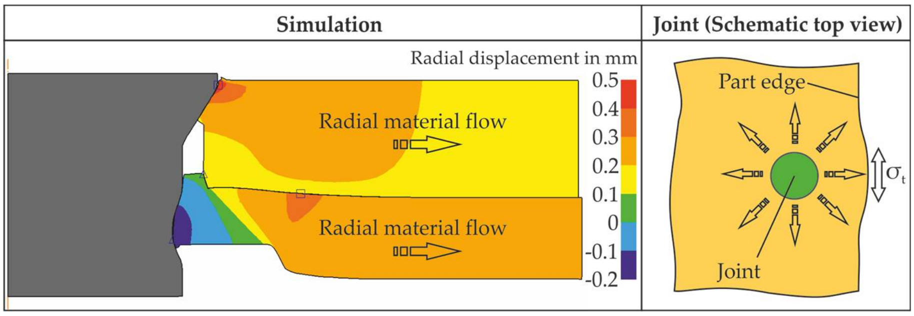

Figure 4. Formation of tangential tensile stresses at the part edge through SPR-S.

However, by the knowledge of the above-mentioned context as well as the specific behavior of 7xxx aluminum alloys with regard to heat treatment the risk of the occurrence of delayed cracks during mechanical joining of 7xxx aluminum components can be reduced by the following approaches [8]:

- Improvement of the surface quality to avoid notches at the part edge, e.g., by laser cutting
- Local regression annealing of the joining zone of the 7xxxer aluminum part as pre-treatment before joining
- Immediate warming treatment of the joined parts, comparable to the cathodic dip painting furnace in automotive production

5. Self-Pierce Riveting with Semi-Tubular Rivets of Carbon Fiber Reinforced Plastics

In general, when positioning the CFRP (t = 2.0 mm) on the punch-side in combination with a more ductile material like EN AW-6016 T6 (t = 2.0 mm) on the die-side, a good joint formation can be achieved by conventional SPR-ST (Figure 5a). The only negative aspect, which can be determined in the cross section (Figure 5a), is that CFRP is deposited under the rivet foot. The microscopic analysis of the CFRP part under the rivet head during a stage of the SPR-ST process provides further important information on the state of the joint (Figure 5b). On the one hand the layers delaminate and on the other the fibers as well as the matrix fracture especially in the area directly next to the rivet. When comparing these results to an idealized SPR-ST joint manufactured with a pre-drilled CFRP part (Figure 5c,d), it can be concluded that most of the fiber and matrix fractures as well as the delaminations result from the piercing of the CRFP through the rivet [9].

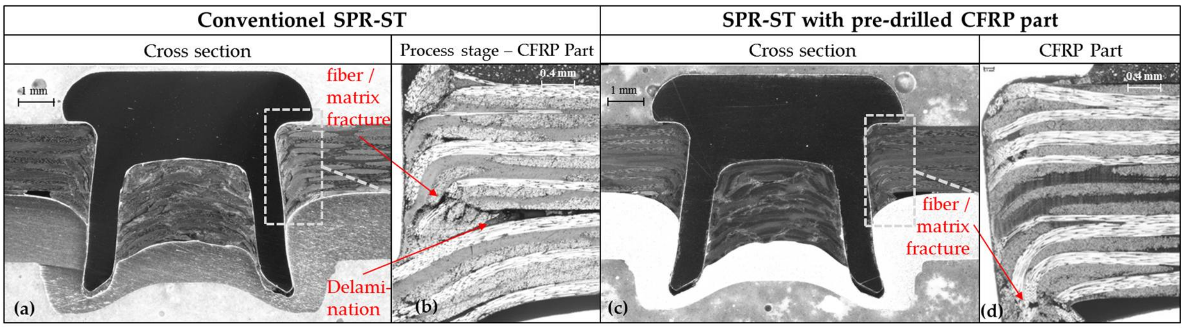

Figure 5. Cross section and analysis of the CFRP part for conventional SPR-ST and SPR-ST with pre-drilled CFRP part.

A better method to visualize the damages in the CFRP is computed tomographic (CT) measurement [10,11]. To increase the accuracy of these measurements (Figure 6) only the CFRP parts from the SPR-ST process and the drilling were investigated separately. To prevent additional damages of the CFRP part from the SPR-ST process, the elevation of the rivet head was removed by turning before the joining process. Following, the CFRP parts were pulled from the rivet shaft.

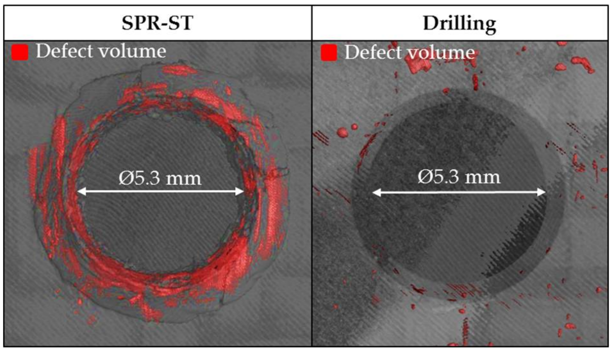

Figure 6. CT measurements of the defect volume in the CFRP parts (in top view) after SPR-ST and drilling.

By measuring the density differences conclusions about damaged areas in the parts can be drawn. This defect volume area, where air inclusions are created as a result of delamination and fiber or matrix fracture, is shown in Figure 6. Unsurprisingly, no additional damages in the CFRP part that was drilled can be detected. In the CFRP part from the SPR-ST process significant damage to the area around the rivet can be determined. Because of the limited resolution of the used CT of 25 μm, it is, however, likely that not all damages in the CFRP parts were detected by this method. In [12,13] was shown, that ultrasonic measurements are able to deliver good results in terms of detecting the defect volume in the CFRP compound. Despite the rather minor influence of the joining process-related damages on the joint strength [9], a reduction of delamination and fiber damage can be advantageous and achieved by the following approaches:

- Application of alternative rivets with adapted foot and enlarged head [13,14]
- Use of a higher blank holder force or an alternative blank holder geometry [14]
- Implementation of an alternative die tool concept to improve the piercing process [9]

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Conflicts of Interest: The authors declare no conflicts of interest.

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