Numerical simulation and experimental validation of self-piercing riveting (SPR) of 6xxx aluminium alloys for automotive applications

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Abstract. Two-dimensional axisymmetric models of the self-piercing riveting (SPR) process consisting of punch, blank holder, die, rivet, upper blank and lower blank were built using the finite element software package simufact.forming\textsuperscript{™}. Three different joint configurations were modelled. An optical measurement system was used for capturing the actual geometries of both the die and the rivet which were then introduced into the simulation model. The stiffness of the riveting pliers was modelled as numerical spring. A combined model of Coulomb friction and shear friction was applied. Both friction coefficients were determined by inverse modelling. The deformation behaviour of the 6xxx aluminium alloy blanks to be joined was described with flow curves extrapolated from results of uniaxial tensile tests. In order to validate the results of the simulations self-piercing riveting experiments using 6xxx aluminium alloy blanks and coated steel rivets were conducted. Force-displacement curves of the punch were captured during the riveting process. Characteristic geometrical features of cross-sections of these joints including horizontal undercut of the rivet, bottom thickness of the lower blank and rivet head overlap were investigated using optical microscopy. The cross-sections of the self-piercing riveting joints obtained from simulations and experiments showed very good geometrical agreement, and just slight differences were observed between the force-displacement curves.

1. Introduction
In order to fulfil the increasing requirements regarding emissions, fuel consumption and performance of modern vehicles, lightweight design is one of the key topics in the automotive industry nowadays. Reducing the weight of the body-in-white is achieved by combining new lightweight materials with innovative manufacturing technologies. However, the increasing variety of materials used in modern vehicles causes new challenges, because different physical and chemical material properties make thermal joining of dissimilar materials quite difficult or even impossible \cite{1}. Therefore, the application of innovative mechanical or hybrid joining technologies is increasing steadily. In particular self-piercing riveting (SPR) has become a common mechanical joining process for lightweight materials in car body manufacturing \cite{2}. SPR enables efficient and reliable joining of similar materials, e.g. aluminium alloy sheets \cite{3}, and of dissimilar material combinations, e.g. aluminium alloy sheets with thermoplastic composite sheets \cite{4} or with steel sheets \cite{5}.

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The variety of rivets and dies available on the market requires reliable routines for determining the optimum rivet/die combination fulfilling the specific requirements of the joint. Ma et al. [5] investigated the influence of four key parameters on the mechanical performance of dissimilar SPR joints using seven sets of different rivet/die combinations. They observed that the ratio between the volumes of the rivet and the die may directly influence specific failures occurring during the riveting process. The potentials of the software packages LS-Dyna and simufact.forming™ to predict the joining performances of aluminium alloy sheets with steel sheets and of 5xxx aluminium alloy sheets, respectively, were investigated by Abe et al. [6],[7] and by Carandente et al. [8]. In both of these studies good agreements between simulation results and experimental data were achieved. Porcaro et al. [9] and Domitner et al. [10] investigated SPR joints of 6xxx aluminium alloys. They modelled the riveting process as well as the joint testing procedures using the software LS-Dyna, and they compared the simulation results with experimental data. In their work the results obtained from the two-dimensional (2D) axisymmetric riveting process model, including joint geometry, stress field and strain field, were the basis for the three-dimensional (3D) models of the destructive joint testing procedures.

The present study investigates SPR of 6xxx aluminium alloy blanks (temper T4) with coated steel rivets experimentally and numerically. Two rivet types (C5.3x4.5, C5.3x6.0) and one die type (5B06) were used for joining blanks of 1.2 mm and 2.5 mm thickness. Riveting experiments including three different joint configurations were conducted. For each of these configurations force-displacement curves of the punch were captured during the riveting process and cross-section specimens of the final joint were produced in order to validate the simulation results. Distinct improvement of the simulation results was achieved by considering the stiffness of the riveting pliers and by using measured 3D geometries of the die and of the rivets. A unified friction model suitable for different contact zones was defined and friction factors were calibrated for each of these zones.

2. Simulation model

2.1. General remarks
Numerical simulation of the SPR process was performed using the finite element software package simufact.forming™ [11] which includes the implicit MSC Marc solver for non-linear applications. SPR of three blank combinations was modelled: 1.2 mm / 1.2 mm, 1.2 mm / 2.5 mm, and 2.5 mm / 2.5 mm. The main process parameters and boundary conditions given in table 1 were derived from the SPR experiments. Punch, die and blank holder were defined as rigid. Since the blanks and the rivet were defined as deformable they were meshed with tetragonal (‘quad’) elements. Due to large deformations occurring at the cutting zone in front of the rivet tip frequent remeshing was necessary in each calculation step, which was triggered by exceeding a predefined value of strain change. The remeshed elements in front of the rivet tip become smaller until the minimum blank thickness is reached to achieve accurate geometrical cutting. The temperatures of the blanks and of the rivet were assumed as constant during the SPR process. This assumption is reasonable, because the process already finishes before the blank temperature increases due to friction heat. Since the riveting pliers were observed to deform elastically during the SPR experiments, a numerical spring with the same stiffness as the pliers was positioned below the die in the simulation model.

2.2. Model geometry
Axisymmetric 2D models which support geometrical cutting features as well as stable meshing and remeshing features were utilized. However, it should be mentioned that axisymmetric 2D models consider neither offset nor tilt of the die due to elastic deformation of the riveting pliers. The actual dimensions of self-piercing rivets, e.g. height, outer diameter, inner diameter or tip radius, may vary distinctly. In order to obtain a representative rivet geometry as input for the simulation model the actual geometries of five rivets were captured using the optical 3D measurement system GOM ATOS III Triple Scan. Based on the results of the five measurements an averaged rivet geometry was created. Figure 1 (left) compares this averaged geometry with the reference geometry of the C5.3x4.5 rivet type provided by the manufacturer. Due to significant differences between these geometries dimensional optimization
was mandatory. As shown in figure 1 (right), the difference between the averaged geometry and the optimized geometry which was then used as input for the simulation model decreased below ± 0.05 mm. The same process was also performed for optimizing the geometry of the C5.3x6.0 rivet type. Furthermore, the actual geometry of the die used for all riveting experiments was captured and compared with the reference geometry provided by the die manufacturer. However, no significant difference between these geometries was observed.

![Figure 1](image1.png)

**Figure 1.** Geometrical difference (mm) between averaged geometry and reference geometry (left) and averaged geometry and optimized geometry (right) of the C5.3x4.5 rivet type.

### 2.3. Material definitions

Uniaxial tensile tests were conducted for characterizing the elasto-plastic properties of the aluminium alloy blanks. Three specimens according to DIN EN ISO 6892-1 were tested for each blank thickness, 1.2 mm or 2.5 mm, respectively. Based on true stress-strain curves derived from the tensile test results (figure 2 left, orange line) flow curves were extrapolated to plastic strains beyond 0.2 using the Hockett-Sherby model [12]. The classic Hockett-Sherby model describes the behaviour of the aluminium alloy used for the investigations quite well for plastic strains below 0.5, but underestimates strain hardening beyond this limit. Thus, the classic Hockett-Sherby model was extended with a linear term to consider sufficient strain hardening (figure 2 left, blue line). The method applied for extrapolating the flow curve to higher plastic strains influences distinctly the deformation behaviour and therefore the piercing behaviour of the blanks in the numerical simulation. Indirectly, this also affects the deformation (i.e. the spreading) of the rivet. The force-displacement curve of the steel rivet was determined by uniaxial compression tests of hollow cylinder specimens cut from the shaft of the rivet. Vaseline was used as lubricant to reduce friction between the polished plane faces of the specimens and the jaws of the Gleeble 3800® machine utilized for testing. The flow curve of the rivet material (figure 2 right, green line) was then determined by inverse modelling of the compression test using the software simufact.forming™.

![Figure 2](image2.png)

**Figure 2.** Extrapolated flow curves of the aluminium alloy blank (left) and of the steel rivet (right). $A = 125$ MPa, $B = 340$ MPa, $C = 20$ MPa, $m = 6.5$ and $n = 0.82$ are the fit parameters for the blank. $A = 1500$ MPa, $B = 1680$ MPa, $m = 25$ and $n = 0.65$ are the fit parameters for the rivet.
2.4. Friction definitions

A combined friction model was applied which assumes that friction stresses increase according to Coulomb’s law until they reach the material’s strength limit. A shear friction law was applied instead of Coulomb’s law beyond this strength limit, because Coulomb’s law would overestimate the friction stresses. The Coulomb friction coefficient, \( \mu \), and the shear friction coefficient, \( m \), were determined by iterative inverse modelling until both the cross-sections of the joints and the force-displacement curves match the experimental results. In particular the deformation of the closing head was observed to depend strongly on the friction condition at the contact area between lower blank and die. Identical values for \( \mu \) and \( m \) were applied for each of the three joint configurations modelled, since identical rivet materials, blank materials and tool geometries were used. The friction coefficients finally used in the model are summarized in table 2. Note that \( \mu < m \) for each pair of components.

| Table 1. Main process parameters | Table 2. Friction coefficients (\( \mu \)) |
|---------------------------------|---------------------------------|
| Punch velocity                  | 100 mm/s                        |
| Blank holder force              | 10 kN                            |
| Stiffness of the pliers         | 25 kN/mm                         |
| Process temperature             | 20 °C                            |
| Friction coeff.                 | blank/ | blank/ | blank/ | blank/ | punch/ |
| blank holder                   | blank | rivet | die   | b. holder | rivet |
| \( \mu \)                       | 0.2   | 0.1   | 0.3   | 0.2      | 0.2   |
| \( m \)                         | 0.4   | 0.3   | 0.45  | 0.4      | 0.5   |

3. Simulation results

The effective plastic strain field that occurs in the aluminium blanks at three distinct steps of the SPR process are displayed in figure 3. At ‘step 1’ the blanks are clamped with constant force between the blank holder and the die in order to reduce bending of the blanks in the following steps. After the rivet is positioned at the top of the upper blank the punch starts to move downwards. At ‘step 2’ the punch force increases slightly while the rivet cuts the upper blank. A drop of the punch force can be observed when the rivet finally pierces the upper blank at the end of ‘step 2’. In this study the ductile 6xxx aluminium alloy is assumed as completely pierced when the remaining thickness of the blank is less than 0.01 mm. At ‘step 3’ the punch force increases again until the punch reaches its final position. High plastic strains beyond 3.0 occur in the zones where the rivet pierces both blanks and where the die and the lower blank touch each other. After releasing the tools at the end of ‘step 3’ the elastic energy stored in the joint is released as elastic springback. The process steps are exemplarily marked in the force-displacement curve shown in figure 4.

![Figure 3. Effective plastic strain (-) occurring in the aluminium blanks at three distinct process steps.](image-url)
4. Experimental validation

4.1. Joint cross-sections and force-displacement curves

Figure 4 compares the simulation results with the SPR experiments for the three joint configurations investigated: 1.2 mm / 1.2 mm (top), 1.2 mm / 2.5 mm (middle), and 2.5 mm / 2.5 mm (bottom). In the left column the joint cross-sections and in the right column the force-displacement curves of the punch are shown. For all of these configurations the joint cross-sections fit generally well. However, the cross-sections of the configuration 2.5 mm / 2.5 mm differ slightly due to the increasing length-to-diameter ratio which reduces the stability of the rivet during the SPR process. Until the rivet pierces the upper blank the curves obtained from the simulations are located above the curves measured during the SPR experiments. However, after piercing the blanks the calculated curves fit well with the measured curves.

Table 3 compares the mean values of characteristic geometrical features which can be determined from the SPR joint cross-sections: the horizontal undercut of the rivet (HU), the bottom thickness of the lower blank (BT), and the rivet head overlap (RO). Since the differences are small the numerical model represents the SPR process quite well.

| Joint configuration  | 1.2 mm / 1.2 mm | 1.2 mm / 2.5 mm | 2.5 mm / 2.5 mm |
|----------------------|-----------------|-----------------|-----------------|
| Geometrical feature  | BT   | HU   | RO   | BT   | HU   | RO   | BT   | HU   | RO   |
| Experiment           | 0.24 | 0.28 | 0.08 | 0.84 | 0.32 | 0.10 | 0.62 | 0.45 | 0.15 |
| Simulation           | 0.20 | 0.28 | 0.09 | 0.86 | 0.28 | 0.08 | 0.57 | 0.52 | 0.13 |
4.2. Hardness profiles
As shown in figure 3, high strains occur particularly in the zone where the rivet pierces the upper blank and penetrates the lower blank. This causes massive local strain hardening of the aluminium alloy blanks. Vickers hardness measurements across the joint cross-section were conducted to validate this effect. Figure 5 shows exemplarily two representative hardness profiles obtained for the joint configuration 1.2 mm / 1.2 mm. Hardness increases from approx. 80 HV0.5 inside the original aluminium blank to approx. 110 HV0.5 at the center of the strongly deformed joint zone.

![Figure 5. Representative hardness profiles for the SPR joint configuration 1.2 mm / 1.2 mm.](image)

5. Conclusions and Outlook
Three configurations of self-piercing riveting (SPR) joints were investigated numerically and validated experimentally. Based on the results of the current study the following conclusions are drawn:

- Comparing the results of the simulations with the riveting experiments shows very good agreement. For each of the three joint configurations investigated just small differences between the cross-sections of the joints and the force-displacement curves of the punch were observed.
- Appropriate friction modelling was identified as most critical factor influencing the results of the simulations. Besides, the method chosen for extrapolating the flow curve to higher strains in order to model strain hardening (in particular for the aluminium sheets) influenced the results distinctly.
- Possible reasons for differences between simulations and experiments are the use of an idealized two-dimensional axisymmetric model geometry, simplifications in the friction model and the lack of information about the actual material behaviour at higher strains and strain rates.
- Three-dimensional modelling of the SPR process would be necessary in order to consider also the influences of punch eccentricity and punch tilt on the joint geometry.
- The results are the basis for numerical investigations of further SPR joint configurations and for numerical determination of the mechanical joint properties.

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