Numerical simulation of thermal supported self-pierce riveting of an ultra high-strength aluminium alloy

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Abstract. This paper will describe the experimental and numerical analysis of the thermal supported self-pierce riveting process of EN AW-6016 T4 into EN AW-7075 T6. In this regard, the experimental process analysis, the development of the simulation model and the evaluation of the FE simulation are discussed.

1. Introduction
Due to the very good strength properties and, compared to steel, the lower density of 7xxx series, aluminium alloys like EN AW-7075 T6 are becoming more relevant for structure parts in car body construction. In aircraft construction these alloys are used for decades. However, due to the higher requirements in automotive industry regarding automation, other technologies for processing this ultra high-strength aluminium alloy have to be found. Currently self-pierce riveting with semi-tubular rivet is the most commonly used joining technique for processing 5xxx and 6xxx series aluminium alloys in automotive industry. Due to the high strength and low ductility of EN AW-7075 T6, the conventional self-pierce riveting process is only limitedly applicable for joining this material. Stresses and strains induced by the joining process can lead to cracking in the EN AW-7075 T6 (Fig. 1: cross section and closing head after colour penetration test CPT), which is not acceptable. [1]

| Process parameters | Cross section | Closing head (CPT) |
|---------------------|---------------|-------------------|
| Punch-sided part:   | Thickness:    |                   |
| EN AW-6016 T4       | s = 1.2mm     |                   |
| Die-sided part:     | Thickness:    |                   |
| EN AW-7075 T6       | s = 2.3mm     |                   |
| Rivet:              |               |                   |
| C 5.3 x 4.0 H4      |               |                   |
| Die:                |               |                   |
| M 10 x 1.5mm        |               |                   |
| Joining force:      |               |                   |
| 74kN                |               |                   |

Figure 1. Cross section and process parameters for conventional self-pierce riveting of EN AW-6016 T4 into EN AW-7075 T6
2. Thermal supported self-pierce riveting

One approach to prevent cracking during the mechanical joining of brittle materials is to apply a thermal superposition of the joining process. Various publications [2, 3, 4] show that this approach, e.g. for the application of joining of magnesium components, leads to improved joining results, but the process time for heating the sheets and an unintentional heating of the tools are challenging. In the process described here an inductor is integrated directly in a ceramic die for heating the sheets. This enables short process time and prevents heating of the joining machine.

![Figure 2. Process principle of thermal supported self-pierce riveting](image)

After the parts are positioned between the joining tools, the die-sided part is heated by the inductor, which is regulated by a pyrometer. After reaching the necessary joining temperature of 250°C, the self-pierce riveting process is performed: 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-sided part and is enclosed inside the rivet. Following, the shape of the die causes the rivet to expand and creates the interlock. At the end, the cavity of the die can be completely filled with material.

3. Simulation models

The considered thermal supported self-pierce riveting process is separated in the heating and the joining of the sheets. In order to be able to represent both process steps numerically with sufficient precision, these two processes were considered separately in the numerical investigation. The setup of the simulation models is shown in Fig. 3.

![Figure 3. 2D simulation models for the heating of the sheets and self-pierce riveting process in DEFORM V11](image)

For the simulation of the heating process (Fig. 3, left), the ambient air also has to be meshed in order to be able to take convective heat losses into account on the one hand and to enable energy coupling into the electrically conductive parts on the other. To reduce the computational effort the symmetry of the objects can be used as simplification. During discretisation, it has to be ensured that
the occurring gradients of the magnetic field progression are mapped realistically [5]. As a guide value for the element side length the electromagnetic penetration depth $\delta$ can be used. At a frequency of 290kHz a value of $\delta \approx 0.2\,\text{mm}$ is calculated. For a good heat coupling the discretisation should be carried out with at least three elements above the penetration depth. Therefore, a minimum element edge length of 0.05mm is used for the heating simulations for the edge areas of the workpiece. The mesh of the air gap should also be finer, since the energy introduced into the workpiece can be mapped incorrectly if the mesh is too coarse. [5] describes a number of at least three elements over an air gap with the width of 0.5mm as suitable value. An ambient temperature of 25°C is assumed for the simulations. Due to the unknown flow conditions and the complex determination, the heat transfer coefficient is generally assumed to be constant in numerical calculations. For stationary air and free convection values of $\alpha = 2\cdot 25\,\text{W/(m}^2\cdot\text{K)}$ can be calculated according to [6]. The exact value is determined on the basis of the experimental data as a fit parameter. The time course of the required generator power comes from measurements of the experimental heating tests.

The calculated temperatures from the inductive heating simulation are mapped onto the mesh of the simulation model for the self-pierce riveting process. In the 2D rotationally symmetric simulation model the rivet and the parts are calculated with elastic-plastic deformation behaviour. To lower the computational effort, the punch, blankholder and die are considered as rigid and are only meshed to calculate the heat transfer. For the implementation of the heat transfer coefficient, a pressure-dependent formulation according to [7] is used:

$$
\alpha = 1.5 + 4 \cdot \left(\frac{\sigma_{\text{kN}}}{k_f}\right)^{0.75} \cdot \left(1 - \exp \left[-10 \cdot \left(\frac{\sigma_{\text{kN}}}{k_f}\right)^{1.5}\right]\right). \tag{1}
$$

Similar to forging, very high contact normal stresses occur at the self-pierce riveting process. Therefore, the friction conditions are calculated by the law of constant friction [8]:

$$
\tau_R = m \cdot k_s \tag{2}
$$

$$
k_s = \frac{\sigma_V}{\sqrt{3}} \tag{3}
$$

The determination of the friction factors $m$ (Fig. 3, right) is done by fitting the simulation with the experimental joining data. The flow curves (Fig. 4) for calculating the plastic deformation behaviour of the sheets were determined by tempered stack upsetting tests. The stacks are conductively heated by the upsetting tools in which the temperature control is carried out.

![Figure 4. Determined flow curves for EN AW-6016 T4 ($s = 1.2\,\text{mm}$) and EN AW-7075 T6 ($s = 2.3\,\text{mm}$)](image-url)
As very high local degrees of deformation are caused in the sheets by self-pierce riveting the experimental data is extrapolated using the HOCKET-SHERBY approach [9]:

\[ k_f = C_1 \cdot \left( C_1 - C_2 \right) \cdot e^{-C_3 \cdot \phi} \cdot C_4 \] (4)

4. Validation

Based on the model parameters described in paragraph 3, the simulation of the heating process of the sheets was carried out and is compared with the experiments in Fig. 5.

![Figure 5. Comparison of experiment and simulation of the inductive heating process](image)

It can be determined that the temperature progression during inductive heating of the sheets is well represented by the simulation model. The die-sided EN AW-7075 T6 requires approx. 4 seconds for heating up to 250 °C in the considered area. The punch-sided EN AW-6016 T4 heats up with a short delay.

The comparison of simulation and experiment of the thermal supported self-pierce riveting process on basis of the joint contour and force-displacement curve shows also good agreement between the numerical calculation and experimental data (Fig. 6).

![Figure 6. Comparison of experiment and simulation of thermal supported self-pierce riveting of EN AW-6016 T4 (s = 1.2mm) into EN AW-7075 T6 (s = 2.3mm)](image)

It can be determined that the thermal superposition of the riveting process prevents the formation of cracks in EN AW-7075 T6 and generates a very good joint formation. In addition, a significantly lower joining force is required in comparison to the conventional self-pierce riveting process (Fig. 1).
5. Results

Based on the validated simulation model, a thermal analysis of different areas of the joint during the thermal supported self-pierce riveting process is possible (Fig. 7).

![Figure 7. Calculated temperature distribution at the end of the setting process (left) and temperature progression in different areas of the joint during and after the joining process (right) for thermal supported self-pierce riveting of EN AW-6016 T4 $s = 1.2\text{mm}$ into EN AW-7075 T6 $s = 2.3\text{mm}$)](image)

In the beginning of the riveting process only the sheets have an elevated temperature of 250°C (Fig. 7, P4 $t = 0\text{s}$). Due to the joining process related transformation of conducted forming work into heat, the temperature of the die-sided sheet raises up to approx. 300°C until the rivet head is set flush with the punch-sided EN AW-6016 T4 (Fig. 7, P4 $t = 0.1\text{s}$). Afterwards the sheets cool down continuously. The largest heat transfer from the sheets to the rivet can be observed at the rivet foot. A maximum of 200°C is reached in this area (Fig. 7, P3 $t = 0.1\text{s}$). In comparison, the heat in the rivet head increases very slowly and reaches only a maximum of approx. 125°C.

This knowledge is very useful for the selection of a suitable rivet coating as well as for the further productivity optimisations of the thermal supported self-pierce riveting of ultra high-strength aluminium alloys.

References

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