Joint Design for Strut Connections in Airplane Structures Produced by Electromagnetic Forming

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Abstract. Electromagnetic forming offers high potential for producing high-quality joints of similar and dissimilar materials. This can be exploited e. g. in aircraft design for assembly of struts. In order to give insight in the interactions between different influencing parameters and their effect on the loadability of the resulting joint in electromagnetic form-fit joining, design of experiments was used in a comprehensive study. Groove parameters (shape, depth, width and edge radius) and the capacitor charging energy were varied in joining experiments considering tubes made of EN AW-2024 (T351) with an outer diameter of 70 mm and, a wall thickness of 1.6 mm together with end parts made of the same material with a diameter of 66.8 mm. The loadability of the resulting compound was evaluated considering axial compression force. One important finding was that triangular grooves can provide highest loadability if relatively deep grooves, well-adjusted groove width and suitable capacitor charging energy are applied. An optimized groove edge radius can contribute to further improvement of the loadability. Numerical simulations on different groove shapes were performed in order to study the development of the forming stages during the process and to explain the trends observed in the experimental study.

Keywords: Joining · Electromagnetic forming · Aluminum

1 Introduction

Aircraft design usually bases on framework structures made of lightweight materials, such as fiber-reinforced plastic, titanium alloys or aluminum alloys. Depending on the specific application, the load bearing capacitance ranges from a few kilonewton up to more than 250 kN [1]. The connections of strut or rod bodies and end parts are frequently complex, which contributes to the typically high costs of the assembled components. Joining by electromagnetic compression offers a promising alternative for realizing connections in an easier way especially if the considered strut or rod bodies are made of aluminium tubes.

When joining by electromagnetic compression, the bond can be based on different mechanisms. Interference-fit joints, based on elastic-plastic bracing of the two joining

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partners [2], and form-fit joints, based on the formation of undercuts [3], can be classified as crimp joints. These are complemented by magnetic-pulse welded joints, where high-speed collision of the two joining partners results in a material bond [4]. Both magnetic pulse welding and crimping can achieve high bond strength under suitable process conditions, so that in mechanical load tests failure occurs in the base material and not in the joint [5, 6].

Crimp connections can be used to join tubular metallic components with metallic [7] or non-metallic [8] joining partners. Interference-fit crimp connections require only slight deformation and no secondary forming elements, such as beads or grooves. Thus, it is particularly suitable for joining materials of poor formability, but impurities significantly impair the strength of interference-fit joints, and a long joint area might be required to achieve high joint strength. Form-fit joints can produce high strength at shorter length, thus saving space and weight, but they require one joining partner with geometric features (grooves or beads), thus increasing joint preparation effort. Magnetic pulse welding can produce high-strength joints with little overlap of the joining partners, but the high collision speed necessary for successful welding requires significantly higher capacitor charging energy than crimp joints. Moreover, an inital distance of several millimeters in-between the joining partners must be provided for acceleration. In tube welding, this distance corresponds to a radial gap, which implies that considerable strain and corresponding ductility of the material is necessary. Against this background, form-fit joining appears particularly attractive for producing struts for aerospace applications with medium load requirements.

Since form-fit joining by electromagnetic compression was invented in the 1960s, several studies on the influence of groove geometries have been carried out for different materials. Bühler and von Finckenstein investigated joining of steel tubes to inner joining partners (mandrels) featuring rectangular grooves. They adjusted the energy so that the deformed tube just reached the bottom of the groove and found that for this condition deeper grooves allow transferring higher force while wider grooves reduce the transferable force [9]. Golovashchenko considered round grooves in form-fit joining of copper tubes. He adjusted the capacitor charging energy in the same way as Bühler and von Finckenstein and confirmed both findings for this scenario [10]. Park et al. focused on form-fit joining of aluminum tubes (EN AW-6063) using rectangular grooves [5]. By applying the same energy independent of the groove measurements, they showed that there is an optimum value for groove depth and width that results in maximum transferable strength. As material thinning can occur at the edge of the groove, the transferable force also depends on the edge radius. Weddeling studied different groove shapes using the same tube material (EN AW-6063) [11]. He found that joint strength was slightly higher for rectangular grooves than for triangular and round ones, but trigangular grooves showed less thinning of the tube material. Furthermore, he proved increasing joint strength with increasing depth for all geometries. Considering width, he showed that increasing values decrease joint strength for round and triangular shapes while there is an optimum width value leading to maximum strength for rectangular grooves. Furthermore, Weddeling proved that higher charging energy increases joint strength. In contrast to Park et al., he found no significant influence of the edge radius on the joint strength. Both Weddeling and Park et al. considered multiple groove joining and showed that joint strength increases with increasing number of grooves.

It can be subsummerized that despite of some general trends there are deviations in the results of the different investigations, which might be attributed to differences in the implementation of the studies, in the considered parameter settings (materials, dimeters, groove dimensions, energies) and in the regarded load case (tension or compression load). A shortcoming is that the studies give no insight in the interactions between different influencing parameters. Therefore, one major aim of this paper is to gain comprehensive knowledge about these interactions in form-fit joining via design of experiments. The novelty of this paper is that interaction graphs are used to illustrate and analyze mutual interdependencies between different parameters. This study is conducted with respect to a specific aircraft application, that is, the assembly of Z-struts. Z-struts carry the passenger floor in large passenger aircraft. Thus, tubes made of EN AW-2024 (T351) with an outer diameter of 70 mm and a wall thickness of 1.6 mm were chosen as outer joining partners and end parts made of the same material with a diameter of 66.8 mm served as inner joining partners (mandrels).

2 Influences and Interactions in Form-Fit Joining

The groove geometry was parameterized, and design of experiments was performed using Cornerstone 7.3 to analyze the influence of the individual parameters and their interactions on the axial compression strength of the compound. Table 1 gives an overview of the parameter ranges considered here. In addition to geometrical parameters, also the capacitor charging energy was regarded as an influencing process parameter.

Table 1. Parameter ranges considered in the experimental study of form-fit joining by electromagnetic compression

Materials		Groove geometry parameters				Capacitor charging energy
Tube	Mandrel	Shape	Width	Depth	Edge radius	
EN AW-2024 (T351)		Rectangular Triangular Round	9–15 mm	2–4 mm	0–2 mm	10–20 kJ

Based on this scope, 32 sets of parameter combinations were selected for experimental investigation. Tubes and mandrels were prepared and joined by electromagnetic compression. For this purpose, a 4-turn coil with a diameter of 82 mm and a length of 91 mm was applied together with a 2-segment fieldshaper, which focused the magnetic field and the corresponding magnetic pressure to a length of 32 mm. Coil current courses were recorded in order to characterize the acting loads during joining. The experimental setup and representative current over time curves are illustrated in Fig. 1 together with exemplary mandrel geometries and joining results. According to visual inspection, joined specimens can be classified as apparently intact and obviously defective, i. e. cracking due to severe local strain in the area of the groove edge occured (Fig. 1d).

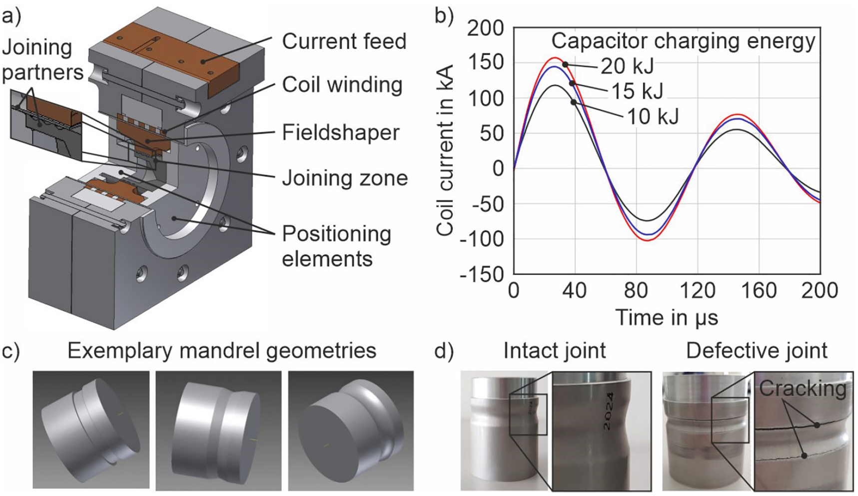

Fig. 1. Experimental setup for form-fit joining (a), measured current courses (b), exemplary mandrel geometries (c) and exemplary intact and defective joining results.

The main load case of Z-struts is axial compression or combined axial compression and bending, while axial tension load is less critical. Therefore, all intact joints were tested by exposing them to axial compression force in a universal testing machine Z100 by ZwickRoell. In order to evaluate the load bearing capacity, force-displacement-curves were recorded during the tests.

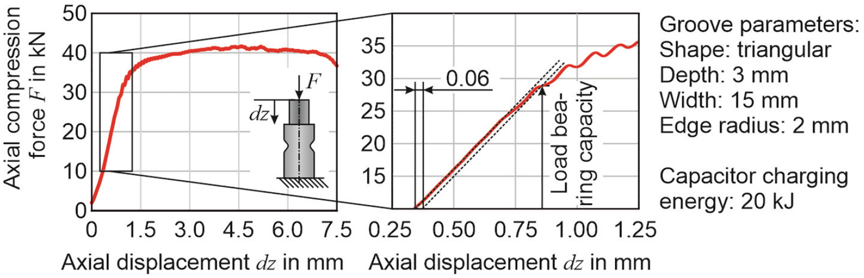

Fig. 2. Force displacement curve recorded during joint testing under axial compression load.

As shown in Fig. 2, the measured curves feature first a linear rise, which can be attributed to the elastic deformation of the tube. This is followed by a non-linear curve section, which indicates plastic deformation of the compound. The wavy shape of the curve in this section might suggest a stick-slip behavior during declamping of the compound. Any slipping or plastic deformation must be considered as failure of the compound. Following the definition of the flow stress in a stress-strain-curve, the load bearing capacity of the compound was therefore defined as the force that corresponds to plastic strain of 0.02% (i. e. approx. 0.06 mm displacement) for the setup considered here (Fig. 2). The load bearing capacity for all parameter sets of this study was used as input data for generating interaction graphs in Cornerstone 7.3 (Fig. 3). For obviously defective specimens the load bearing capacity was set as 0 kN.

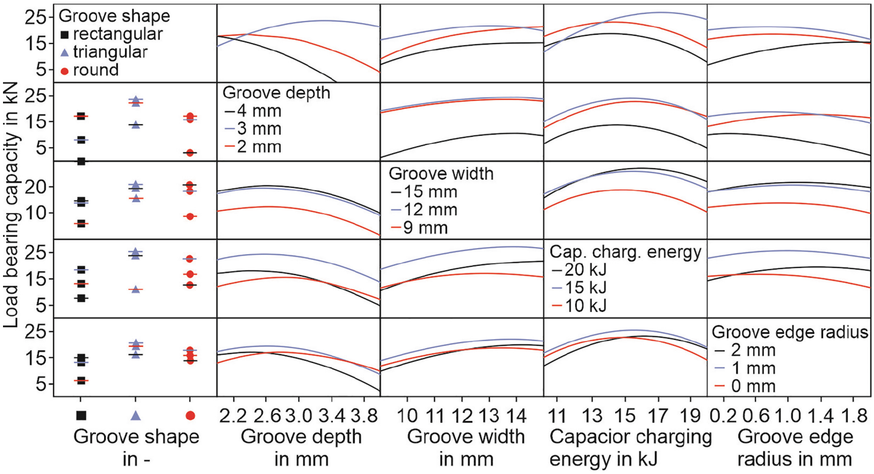

Fig. 3. Interaction graphs for the load bearing capacity of the form-fit joints.

The determined interaction graphs show that for all considered parameters there are optimum values leading to maximum load bearing capacity of the compound. In many cases these optimum values vary with the other parameters clearly proving the relevance of their interactions for process design. Taking the optimum depth as an example, a clear dependance on the groove shape can be detected. For low depth, rectangular grooves lead to highest load bearing capacity while round groove geometries are beneficial at medium depths and triangular grooves can transfer highest loads, but this advantage becomes relevant at high groove depths only. Furthermore, the optimum groove depth slightly decreases with increasing capacitor charging energy and groove edge radius. These correlations are in good agreement with [11], where joints based on triangularly shaped grooves were found to be less susceptible to thinning than rectangular or round ones. Similarly, also the optimum width of the groove is different for different groove shapes. It is independent of the groove depth but rises slightly with increasing capacitor charging energy and groove edge radius. The optimum edge radius is significantly higher for rectangular grooves compared to triangular and round ones. It increases slightly with increasing width and more significantly with increasing energy, while it decreases with increasing depth. The last point might be explained as load bearing capacity can benefit from both – larger contact areas, which accompany higher radii and more significant undercut. In case of low depth, contact area seems to be the decisive parameter, while for higher depth the extend of the undercut is more important. Concerning energy, especially taking the advantages of triangular groove shapes requires relatively high values, while the interactions with the other parameters are less important.

3 Detailed Comparison of Form-Fit Joining with Triangular and Round Groove Shapes

As triangular grooves enable highest joint strength closely followed by round grooves, these geometry variants were examined in more detail via metallographic analysis and numerical simulation was performed to visualize the process in terms of time. For this purpose, a process model was set up in LS-Dyna and coupled electromagnetic and structural mechanical simulations waere performed. For validating the simulation, the outer contour of the joint parts was measured using a 2D/3D Laser Profiler LJ-X8000 by Keyence and compared to the numerically determined result. Figure 4 shows the numerical model and proves that numerically and experimentally determined contours are in good agreement with each other. The remaining deviation can be attributed to tolerances in the tube measurements and to the modelling of the mandrel as rigid body, which disregards all potential elastic deformation.

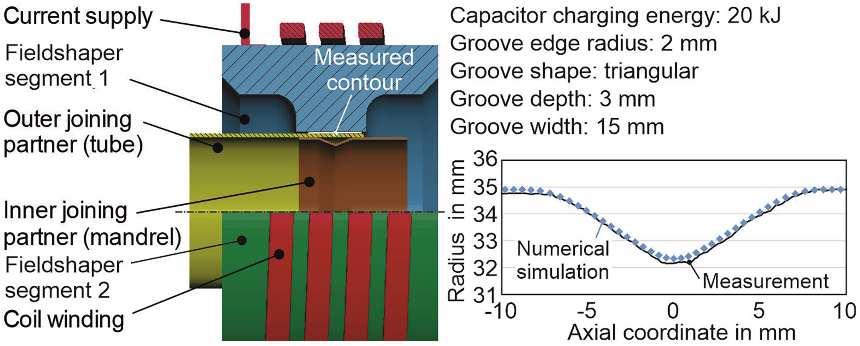

Fig. 4. Numerical model and exemplary comparison of experimentally and numerically determined final contours of the compound.

Figure 5 illustrates the course of the deformation process based on selected forming stages and compares the final stage with a micrograph of the embedded compound. Both – simulation and microscopic examination – show that electromagnetic compression produces a well-formed undercut and that the outer joining partner aligns well to the inner one. The final shape is in good agreement with results determined via x-ray analysis in [11]. In case of the triangular groove shape minor deficits in the alignment of tube and mandrel are located in the center of the groove because the complete filling of a sharp-edged cavity requires bulk sheet metal forming [12] and the associated extremely high forces were not achieved here. In case of the round groove shape there are deficits especially in the areas between the center and the edge of the groove. Here the tube lifts of the mandrel due to tensile forces generated when shaping the center area of the groove. Altogether, the final contact area is larger in case of triangular grooves, which explains that this geometry variant enables highest loadability of the compound. Furthermore, Fig. 5 shows that the deformed tube is not symmetrical in the area of the groove. This effect can be explained as the joining process takes place close to the end of the tube.

The resistance against axial material flow is lower on the short side of the tube (i. e. the right hand side in Fig. 5) and therefore more material is drawn into the groove from this side compared to the long side of the tube.

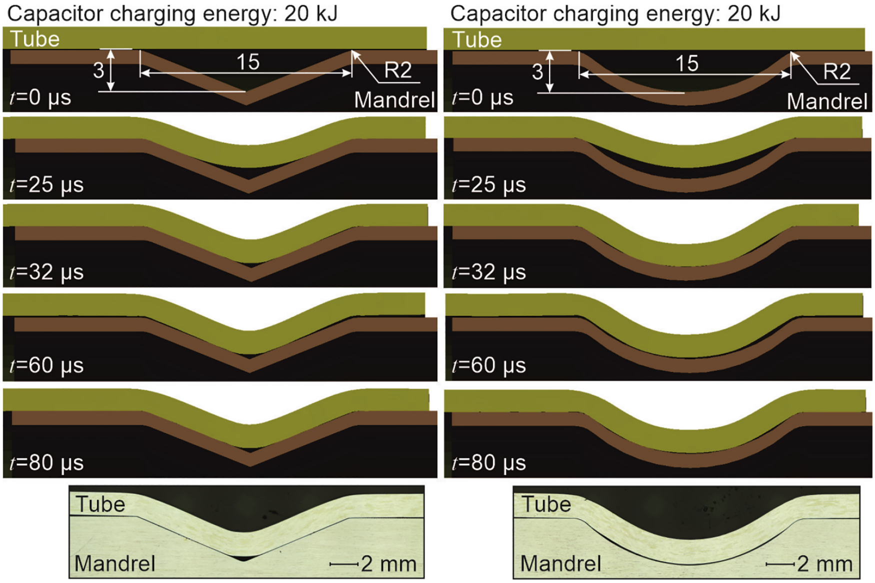

Fig. 5. Numerically determined process stages during form-fit joining with triangular and round grooves and micrographs of corresponding experimental results.

4 Conclusions and Outlook

Design of experiments was performed to gain comprehensive knowledge about influencing parameters on the maximum load bearing capacity in form-fit joining by electromagnetic compression. It was found that all considered parameters feature optimum values providing maximum load bearing capacity and there are mutual interdependences between different the parameters, so that the optimum values can vary with the other parameters. The most significant relations concern the groove shape. Triangular grooves can transfer highest loads, but this requires relatively deep grooves and well-adjusted groove width and capacitor charging energy. At low depths rectangular grooves should be preferred and at medium depths round grooves are beneficial. Especially in case of rectangular grooves, an optimized groove edge radius (i. e. a relatively high one for rectangular grooves) can contribute to further improvement of the load bearing capacity. Numerical process analysis provided deeper insight in the process stages. It proved that deficits in the formation of the undercut manifest in different areas for different groove shapes leading to different contact areas and revealed asymmetries due to differences in the free tube length next to the forming zone.

This study is the start of a three-step joint design strategy for the production of Z-struts. In a forthcoming second step, the influence of number and arrangement of grooves will be investigated. Finally, the mandrel will be drilled hollow to reduce its weight and the influence of the remaining wall thickness on the transferable load will be studied. Numerical analysis will accompany all steps of the design process to get deeper understanding of the process and the resulting joint properties.

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