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Numerical and experimental analysis of struts joined by electromagnetic forming for aircraft applications

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Abstract. Joining by electromagnetic forming can provide high-strength connections of tubes and connector parts from different materials. In order to qualify this technology for manufacturing components made of high-strength aluminum alloys typically used in aircraft manufacturing a parameter study was performed on form fit joining of tubes (outer diameter: 70 mm, wall thickness: 1.6 mm) and mandrels (diameter: 66.6 mm) both made of EN AW-2024 (T351). Since some aircraft applications, e. g. the so-called z-struts, which support the passenger floor of the airplane, are related to high axial compressive loads and medium axial tensile loads, this load scenario was considered. In order to increase especially the compressive load-bearing capacity, joint configurations featuring direct support of the tube end via a step or a shoulder of the joining partner were designed and investigated. The axial support can increase the transferable compressive load, while the tensile load remains largely unaffected. Attention must be paid to the gap between tube end and axial support, which cannot be fully avoided due to axial material flow during the electromagnetic joining process. Bending the tube end into a groove providing axial support of the tube end enables compressive load-bearing capacities, which can approximate the strength of the tube material. Here, increasing bending angles improve the load-bearing capacity under tensile force, but reduce the transferable compressive load. Multiple groove configurations can provide acceptable load bearing capacity considering tensile and compressive load. Numerical simulation can predict the general behavior of components joined by electromagnetic forming, help to understand the damage mechanisms of the joint and allow identifying trends for joint design.

Introduction

The implementation of lightweight design strategies has been in the focus of research for many years. Aerospace industry has taken a pioneering role and still remains a driver for innovation in this field. Developments include the application of materials with particularly high lightweighting potential, such as high-strength aluminum alloys, which have not been widely used in other industries due to the cost structure. Struts and tie rods made of these materials are assembled to build up light frameworks. In this context, joining of tubes and hollow profiles to connector parts is a relevant issue as the resulting connections must be able to withstand forces of up to 250 kN, depending on the specific application in the airplane [1].

Joining by electromagnetic forming is known as an energy- and resource-efficient technology, which is especially suitable for manufacturing high strength joints from similar and dissimilar materials without additives or auxiliary joining elements [2]. The technology invented by Harvey and Brower in the early 1960s [3] uses the energy density of pulsed magnetic fields to apply Lorentz Forces, which accelerate and deform a workpiece made of electrically conductive material. For this purpose, a capacitor battery is charged to a defined voltage and then discharged via a so-called tool coil or inductor, thus imposing a transient highly damped sinusoidal current,

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which induces a magnetic field and a counter-current in the electrically conductive workpiece. The interactions of current and magnetic field result in the above-mentioned Lorentz forces, which form tubular or sheet metal workpieces at velocities of up to 500 m/s and strain rates of up to 10^5/s, thus increasing formability of many materials [4].

One of the most promising application fields of electromagnetic forming is joining of aluminum tubes to connector parts. Comprehensive studies dedicated to process analysis and joint design have been carried out considering aluminum alloys from the 6000 series, which are frequently used for series production in the automotive industry. These involved all three joining mechanisms facilitated by electromagnetic forming, specifically interference-fit joining (e.g. [5], [6]), form-fit joining (e.g. [7], [8]) and magnetic pulse welding (e.g. [9], [10]). More recently, the authors of this article have extended the research to higher strength aluminum alloys, specifically EN AW-2024 (T351) [11]. They pointed out that form-fit joining is particularly promising for producing struts for aerospace applications with medium load requirements and investigated the effects of groove parameters (shape, depth, width, and edge radius) and the capacitor charging energy on the load-bearing capacity of the resulting joint in terms of axial compression force. Here, triangular grooves can provide highest load-bearing capacity if groove depth, width, and edge radius as well as capacitor charging energy are well chosen allowing formation of a distinctive undercut without pre-damaging the tube at the edge radius. [11]

However, the load-bearing capacity of conventional single groove configurations (see Fig. 1a) is limited, so that further improvement of the joint design is necessary. Under pure axial compression load, supporting a straight cylindrical tube by a shoulder of the inner mating part (mandrel) as shown in Fig. 1b variant 1 can be expected to be a favorable solution. However, this setup cannot transmit noteworthy tensile forces, while typical requirement profiles in the field of aircraft construction usually include at least moderate axial tensile loads. Therefore, this paper analyzes how the compressive and tensile load-bearing capacities of form-fit joints produced by electromagnetic forming are affected by different joint geometries and arrangements including such an axial support. As numerical simulation in [11] showed that the position of the groove in relation to the tube end can influence the axial material flow into the groove, this study considers grooves arranged at some distance to the tube end (see Fig. 1b variant 2), grooves arranged directly at the end of the tube and (see Fig. 1b variant 3), and combinations of these groove types (see Fig. 1b variant 4).

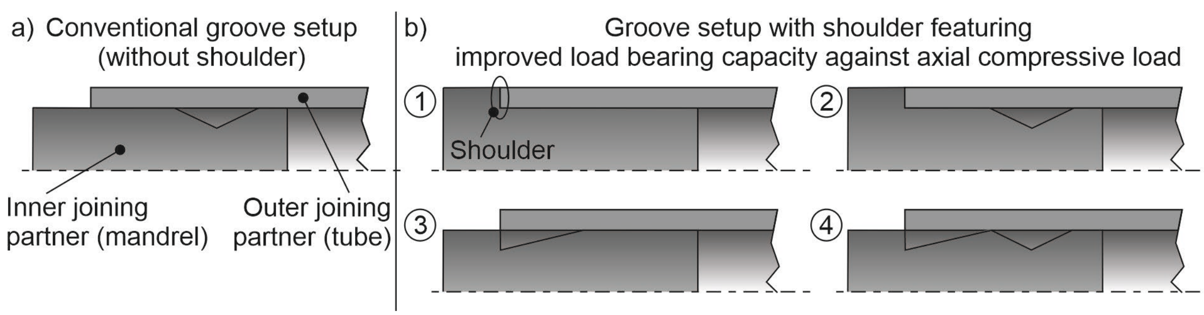


Figure 1. Different types of groove geometries and arrangements.

Experimental setup and numerical modelling

Complementary numerical and experimental investigations are carried out to analyze the correlations described above. Similar to [11], tubes and mandrels made of EN AW-2024 (T351) are regarded. The tubes feature an outer diameter of 70 mm and a wall thickness of 1.6 mm while the outer mandrel diameter is set to 66.6 mm. For joining by electromagnetic forming 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. This inductor system is used with a pulsed power generator featuring the electrical properties listed in Table 1. All experiments and simulations considered in this paper were performed using a capacitor charging voltage of 11 kV.

Table 1. Properties of the considered pulsed power generator.

Maximum capacitor charging voltage	Inner resistance	Capacity	Inner inductivity
25 kV	5 mΩ	330 μF	100 nH

The resulting joints were evaluated via axial push out test and tensile tests, both performed on a universal testing machine Z100 by ZwickRoell at a velocity of 4 mm/min. During the tests, the forces were recorded using a load cell and the corresponding displacement was observed via the crosshead extension. The different test setups are illustrated in Fig. 2. For compression test the specimen (i. e. the tube joined to a mandrel at one end) could be easily inserted between the parallel contact surfaces of the sample holders to apply the forces. For the tensile tests, the tubes were joined to mandrels with attached clamping devices at both ends in order to enable proper load application. The recorded force-displacement-curves in such tests are typically characterized by an initial linear rise followed by a non-linear progression as qualitatively shown in Fig. 2 [11]. The transition from the linear to the non-linear curve section indicates the onset of plastic deformation and the corresponding force was interpreted as load-bearing capacity of the specimen L. To evaluate the further optimization potential of the joint, this load-bearing capacity can be referred to the maximum force that the weaker joining partner (i. e. usually the tube) can transfer without plastic deformation. The latter corresponds to the product of yield strength $R_{p0.2}$ and cross section A (see equation 1). When this relative joint quality indicator K approximates 100%, the load-bearing capacity of the joint approximates that of the surrounding structure and further optimization of the joint brings no additional benefit for the component.

$$K = \frac{L}{R_{p0,2} \cdot A} \tag{1}$$

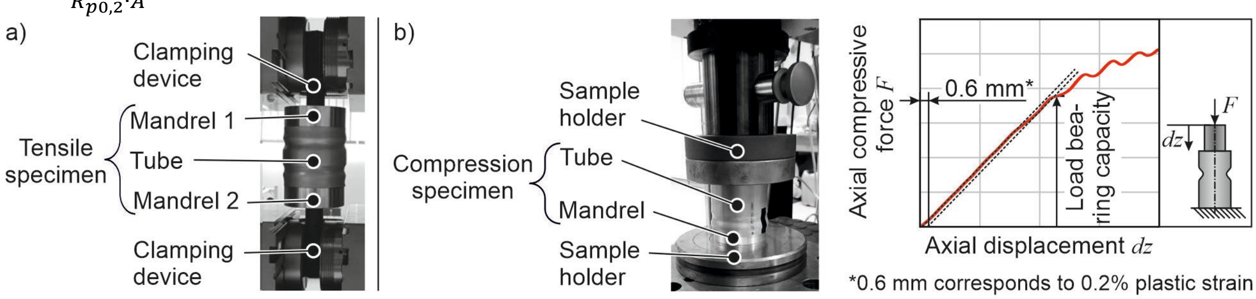


Figure 2. Experimental setup for a) axial tensile and b) axial compression test.

Numerical modeling and simulation covered both, joining by electromagnetic forming and loading of the joint with axial compression or tensile force in order to quantify the load-bearing capacity. Electromagnetic forming was represented by a coupled electromagnetic and structural mechanical simulation in LS-Dyna [12]. Thereby processes in solid bodies were calculated using finite element methods, while the surrounding air was considered using boundary element methods. All parts were modelled with 8-point hexahedron solid elements. The time step size for coupled simulations was 20 ns. The corresponding model is depicted in Fig. 3. It contains the inductor system, i. e. the tool coil including the fieldshaper, both modeled as rigid copper bodies with an electrical conductivity of 49.6 MS/m, the tube, and the mandrel, both modeled as elasto-plastically deformable aluminum bodies (von Mises material) with a measured flow curve and strain rate scaling and with an electrical conductivity of 29.5 MS/m. The pulsed power generator is represented by its electrical parameters (capacitor charging energy, capacitance, inner inductivity and inner resistance) according to Table 1.

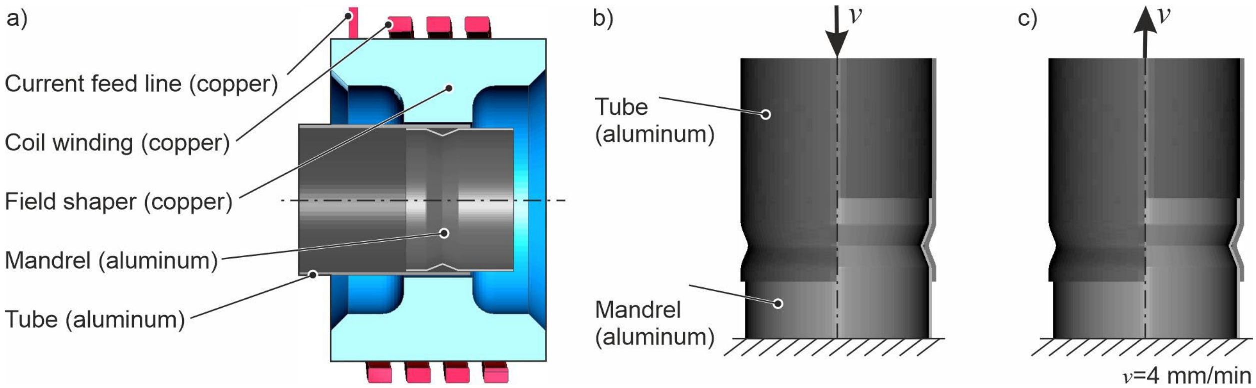


Figure 3. Numerical models for simulation of joining by electromagnetic forming (a) and testing of the joint under axial compression load (b) and tensile load (c)

Numerical simulation of the mechanical loading of the joined specimen was also performed in LS-Dyna using implicit calculation. The model for evaluation of the load-bearing capacity is relatively simple, containing only the tube and the mandrel. All parameters regarding the mechanical behavior were adopted from the preceding electromagnetic forming simulation. Furthermore, all information relevant regarding the forming history of the parts (i. e. especially the local distribution of stresses and strains in tube and mandrel after joining) are transferred. The time step size was automatically adapted between 10 ns and 1 s. Tensile and compression forces, respectively, are applied as boundary conditions, so that all elasticities from the experimental testing setup are disregarded.

Influence of axial support of the tube end on the component load-bearing capacity under axial tensile and compression load

To investigate the influence of an axial support of the tube end on the load-bearing capacity of a form-fit joint produced by electromagnetic compression, a triangular groove with a depth of 3 mm, a width of 15 mm and a groove edge radius of 0.6 mm is selected as reference. This geometry was analyzed in detail in [11] and provides relatively high compressive-load-bearing capacity for the conventional joint configuration (i. e. without support of the tube end). This configuration is now supplemented by an additional step in the mandrel, providing axial support of the tube end (see Fig. 4) and both variants of the configuration (with and without axial support) are joined and then exposed to axial tensile and compression load in numerical simulation.

Regarding the electromagnetic joining process, it is important to consider the axial material flow. Although the high forming velocity in combination with inertia effects causes the material to flow predominantly in thickness direction, thus causing increase of the tube's wall thickness if the diameter is reduced in joining by electromagnetic tube compression, axial material flow cannot be completely disregarded [13]. Consequently, the tube end slightly recedes from the mandrel during filling of the groove, so that a small gap occurs. In this specific case, the predefined initial gap in the numerical simulation was set to 1 µm and, due to axial material flow, after joining by electromagnetic forming a gap of 0.24 mm results. However, the ratio of axial and radial material flow depends on the geometric conditions such as the length of the deformation zone and its distance to the end of the workpiece [13]. In an experimental implementation, gap widths in the range of several tenths of a millimeter and slight variations of this gap-width due to positioning inaccuracies must be expected.

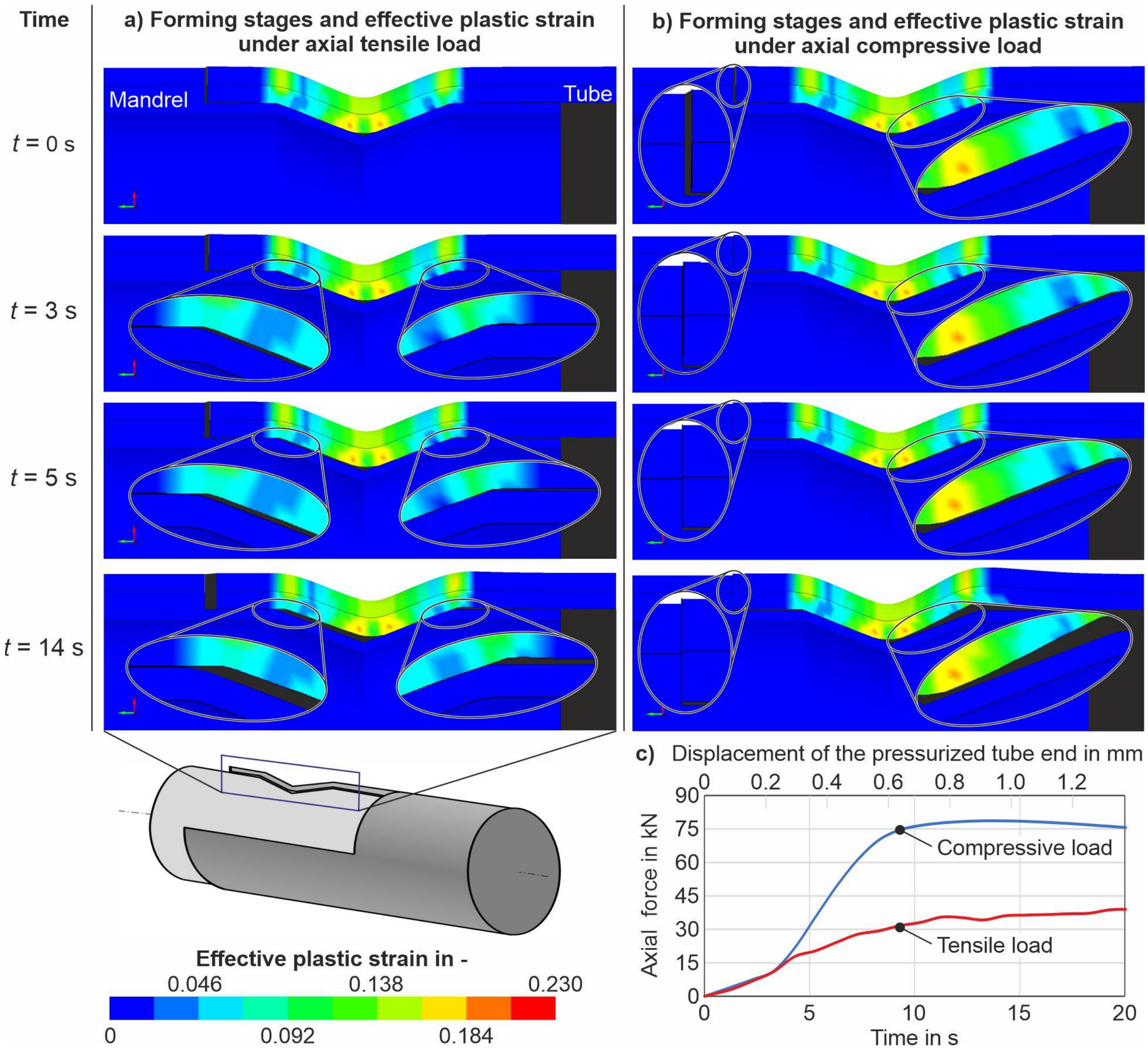


Figure 4. Tube deformation stages under axial tensile (a) and compressive (b) load and corresponding force-displacement-curves.

Under axial tensile load, this effect and the modification of the mandrel in terms of adding a step for support of the tube end has no significant effect. The tube is pulled out of the groove and consequently, the tube radius expands again as shown via representative forming stages during load testing depicted in Fig. 4a. Due to the locally increased strength and stiffness in the region, where the undercut was formed, the generated tube shape remains wavy. The corresponding force-time- and force-displacement curves show the expected approximately linear rise at the beginning, which is then followed by a non-linear curve section. The load-bearing capacity under axial tensile load L_{tensile} is approximately 28 KN, which corresponds to a quality indicator K_{tensile} of 26.6 %. The loading process and the load-bearing capacity of the component is the same as in case of the conventional joint setup without the additional step in the mandrel.

Under compressive load, however, the situation is different as shown in Fig. 4b. At the beginning of the process, the tube is shifted towards the mandrel's shoulder. During this time, the tube lifts from the groove flank facing away the tube end and slides over the groove flank facing the tube end. In the force-time and force-displacement curves this behavior is characterized by a moderate linear rise to approximately 10 kN, which can be attributed to friction. This curve section is followed by another linear section with higher gradient, which can be attributed to elastic deformation of the material after closing of the initial gap of 0.24 mm, when the tube end is supported by shoulder of the mandrel. The load-bearing capacity under axial pressure load $L_{pressure}$ is 35 kN, which corresponds to a quality indicator $K_{pressure}$ of 33.3 %. This means, that compared to the conventional groove configuration analyzed in [11] with a load bearing capacity of 26 kN an improvement of nearly 35% of the load bearing capacity was obtained while the quality indicator still rised by 10%.

Influence of groove configurations arranged at the tube end on the component load-bearing capacity under axial tensile and compressive load

In the next step, form-fit joining with grooves at the tube end was investigated. For this purpose, the geometry depicted in Fig. 5 is regarded and groove width and height were varied in a numerical parameter study in order to identify the influence on the load-bearing capacity and the quality indicator for the joint design. Fig. 5 illustrates these values plotted as functions of the angle α.

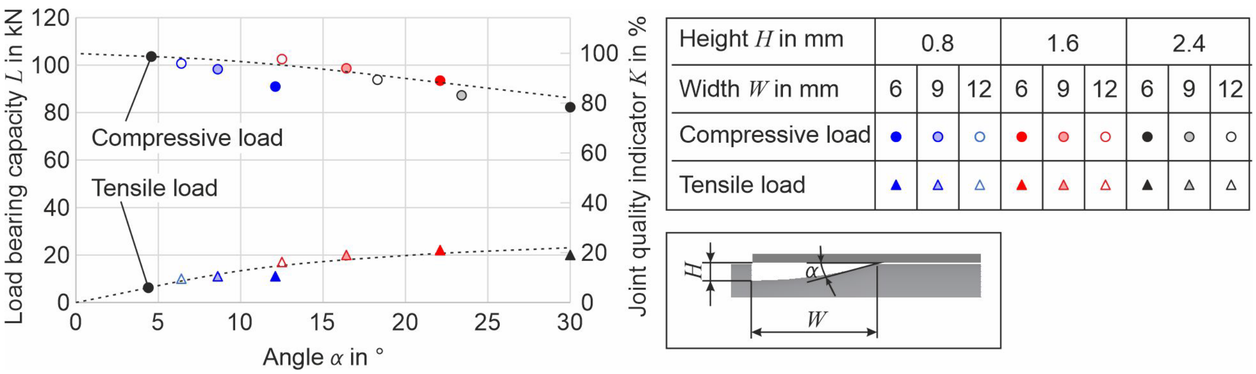
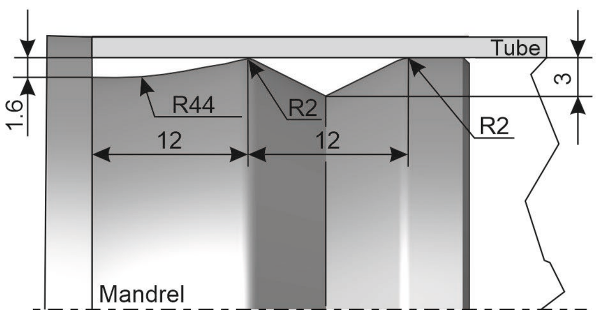


Figure 5. Geometry for investigation of groove configurations arranged at the tube end and corresponding load bearing capacities and quality indicators for the joint design.

Obviously, the load bearing capacity of these configurations under axial compression load is much higher compared to conventional grooves without support of the tube end and compared to the triangular groove setup with support of the tube end presented above. In some cases, the load-bearing capacity of the tube material is even approximated to just a few percent. When comparing the different parameter combinations, it turns out that for the same height H, the forces decrease with decreasing width W and correspondingly increasing angle α. Similarly, also a general trend of decreasing force-bearing capacity with increasing angle can be observed. A possible reason is, that force flow is more deflected in case of higher α-values and at the same time the overlap length between the tube and the mandrel is decreased with decreasing groove width, which results in lower surface friction. Moreover, in case of similar angles a groove height of 1.6 mm seems to be beneficial. This advantage is especially significant in comparison to the higher value of 2.4 mm, but the trend can also be recognized when comparing the lower value of 0.8 mm. For every groove length considered here a height of 1.6 mm, which corresponds to the wall thickness of the tube, leads to maximum transferable force. Considering tensile load, the correlations related to the angle α are reversed. The load-bearing capacity and the quality indicator for the joint design increase with increasing angle and correspondingly increasing undercut formation.

Influence of multiple groove configuration on the component load-bearing capacity under axial tensile and compressive load

Due to the opposing trends, observed in the preceding section a compromise regarding the load-bearing capacities under tensile and compression load must be found, when designing a joint for a specific application. Considering z-struts (i. e. the struts carrying the passenger floor in a passenger aircraft) as a demanding application from aircraft industry, which requests high compressive-load-bearing capacity and medium tensile-load-bearing capacity, none of the above mentioned solutions is directly applicable. Therefore, in the next step, a combination was tested in order to combine the acceptable load-bearing capacity under axial tensile load from the triangular groove and the better load-bearing capacity under axial compressive load from the groove arranged at the tube end. Fig. 6 shows the resulting double groove configuration. The two grooves are positioned without distance in-between them in order to shorten the overlap length of tube and mandrel and the corresponding weight of the component as much as possible. The width of the triangular groove implemented here was slightly reduced compared to the measurements in the investigations presented above, because according to [11], this geometry provides highest compressive load bearing capacity for the conventional joint configuration (i. e. without support of the tube end). The width of the groove at the tube's end was adjusted to enable joining the complete groove configuration in one electromagnetic forming process using the inductor system including the fieldshaper with 32 mm long concentration area. Numerical simulation of the electromagnetic forming and testing of the joint provided the load bearing capacities and joint quality indicators listed in Fig. 6. These results show that the combination of the two grooves allowed obtaining nearly the high load-bearing capacity under compressive load provided by the groove at the tube and nearly the sufficiently high load-bearing capacity under tensile load achieved earlier form the triangular groove at the same time.



Load bearing capacity
under axial compression load: $L_{\text{compression}}$ = 80 kN
under axial tensile load: L_{tensile} = 27 kN

Joint quality indicator
under axial compression load: $K_{\text{compression}}$ = 76%
under axial tensile load: K_{tensile} = 25%

Figure 6. Multiple groove configuration and corresponding evaluation parameters.

For validation purposes mandrels featuring the double groove configuration were manufactured and joined with tubes in electromagnetic forming tests. Afterwards several joined components were exposed to tensile and compression tests and others were examined via metallographic analysis. Fig. 7 compares experimental and numerical results.

Considering the final shape of the joint, experimental and numerical results are in relatively good agreement. Especially the degree of filling of the triangular groove corresponds well, while alignment of the tube to the mandrel at the end of the second groove and at the inner edge of the mandrel is a bit overestimated in the simulation. The final shape in the experimental results suggests that springback happened, which was not exactly reproduced in the numerical simulation.

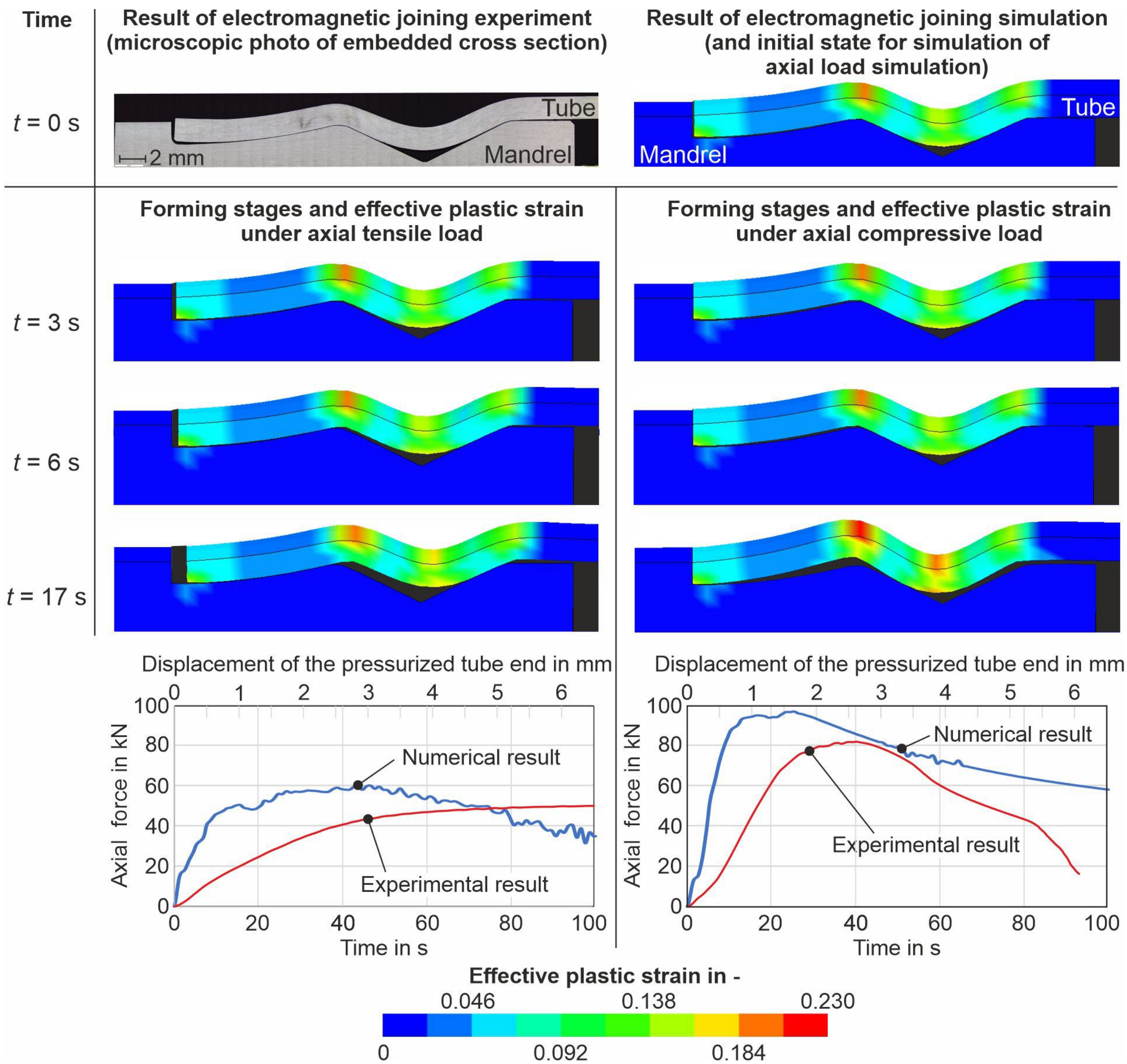


Figure 7. Comparison of experimental and numerical results concerning final shape of the joint, simulated deformation stages under axial tensile and compression load, and corresponding force-displacement-curves under tensile and compressive load.

Concerning the force displacement curves under both, tensile and compressive load, the courses of experimental and numerical results are in good qualitative agreement. The most obvious deviation concerns the slope of the rising curve. This can be attributed to the simple displacement measurement via the crosshead extension, which includes elastic deformation of the clamping and the testing machine, while the numerical simulation considers the displacement directly at the specimen end, disregarding all elasticities in the rest of the test setup and is therefore more meaningful. This explanation is strengthened by the fact that the deviation is higher under tensile load, because here the clamping devices bring additional elasticities at both sides of the specimen.

Due to this shortcoming of the experiment the load bearing capacity under tensile load was not reached until 100 s, so that the testing sequence was extended accordingly to obtain all relevant data. Fig. 7 shows that considering the load-bearing capacity, the simulation can predict the ratio of the different values under tensile and compressive loads, but it slightly overestimates the absolute achieved values. This might be attributed to the overestimated contact surface (due to inaccurate simulation of the springback), which is relevant for calculating the friction forces or to the material model, which was taken from earlier investigations on sheet material made of the same alloy and exposed to the same heat treatment. According to [14], this procedure is standard in simulation of forming processes using tube material, but it can cause significant deviations. The damage mechanism in the joint is slipping, which well predicted by the simulation.

Summary and conclusion

Joining by electromagnetic forming is known to be a technology that can provide high-strength connections of tubes and fittings from different materials including conventional aluminum alloys. Recently, attempts were made to qualify the process for high-strength aluminum alloys in order to enable manufacturing typical components for aerospace industry. Such applications frequently require transfer of high compressive and medium tensile load. In order to fulfill this requirement scenario and specially to enhance the load-bearing capacity under compressive axial loading, different joint configurations featuring direct support of the tube end via a step or a shoulder of the joining partner were designed and investigated. Numerical parameter studies simulating the electromagnetic joining process and the subsequent loading of the joined component with axial tensile and compressive force were carried out and the results were interpreted as load-bearing capacity and evaluated via a quality indicator for joint design. Experimental validation was performed via electromagnetic forming tests followed by axial tensile and compression tests. The following conclusions were found:

- Enhancing a conventional e. g. triangular groove configuration by an axial support can increase the transferable compressive load. Attention must be paid to the gap between tube end and axial support, which cannot be fully avoided due to axial material flow during the electromagnetic joining process.
- Bending the tube end into a groove to axially support the tube end can even provide load-bearing capacities against axial compression which approximate the strength of the tube material. The load-bearing capacity under both, tensile and compressive load, depends on the bending angle α. Increasing α -values improve the load-bearing capacity under tensile force, but reduce the transferable compressive load, so that a compromise must be found depending on the specifically required loadability profile.
- Multiple groove configurations can exploit the advantages of both mentioned groove types to a large extend, thus providing a promising solution for typical aircraft applications.
- Numerical simulation can predict the general behavior of components connected via form-fit joint by electromagnetic forming under axial tensile and compressive load. Thus, it helps to understand the damage mechanisms of the joint and allows identifying trends for joint design, although the quantitative prediction of the load-bearing capacity slightly overestimates the experimental results.

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References

[1] Information on http://www.gmt-gmbh.de

[2] V. Psyk, D. Risch, B.L. Kinsey, A.E. Tekkaya, M. Kleiner, Electromagnetic forming - a review, Journal of Materials Processing Technology 211 (2011) 787-829. https://doi.org/10.1016/j.jmatprotec.2010.12.012

[3] G.W. Harvey, D. Brower, U.S. Patent 2,976,907. (1961).

[4] S.F. Golovashchenko, Material formability and coil design in electromagnetic forming, Journal of Materials Engineering and Performance 16 (2007) 314-320. https://doi.org/10.1007/s11665-007-9058-7

[5] M. Kleiner, M. Marré, C. Beerwald, W. Homberg, D. Löhe, P. Barreiro, V. Schulze, Investigation of force-fit joints produced by electromagnetic tube compression, Annals of the German Academic Society for Production Engineering WGP 13 (2006) 227-230.

[6] M. Geier, E. Paese, R. Rossi, P. A. R. Rosa, R. P. Homrich, Experimental Analysis of Interference-Fit Joining of Aluminum Tubes by Electromagnetic Forming, IEEE Transactions on Applied Superconductivity 30 (2020). https://doi.org/10.1109/TASC.2020.2972499

[7] C. Weddeling, S. T. Woodward, M. Marré, J. Nellesen, V. Psyk, A. E. Tekkaya, W. Tillmann, Influence of groove characteristics on strength of form-fit joints, Journal of Materials Processing Technology 211 (2011) 925-935. https://doi.org/10.1016/j.jmatprotec.2010.08.004

[8] Y.B. Park, H.Y. Kim, S.I. Oh, Design of axial/torque joint made by electromagnetic forming, Thin-Walled Structures 43 (2005) 826-844. https://doi.org/10.1016/j.tws.2004.10.009

[9] R.N. Raoelison, D. Racine, Z. Zhang, N. Buiron, D. Marceau, M. Rachik, Magnetic pulse welding: Interface of Al/Cu joint and investigation of intermetallic formation effect on the weld features, Journal of Manufacturing Processes 16 (2014) 427-434. https://doi.org/10.1016/j.jmapro.2014.05.002

[10] H. Yu, Z. Xu, Z. Fan, Z. Zhao, C. Li, Mechanical property and microstructure of aluminum alloy-steel tubes joint by magnetic pulse welding, Materials Science & Engineering: A 561 (2013) 259-265. https://doi.org/10.1016/j.msea.2012.11.015

[11] V. Psyk, M. Linnemann, M. Henkel, V. Kräusel, M. Dix, Joint design for strut connections in airplane structures produced by electromagnetic forming, Proceedings of the 14th International Conference on the Technology of Plasticity - Current Trends in the Technology of Plasticity (2023) 149-156. https://doi.org/10.1007/978-3-031-41341-4_16

[12] P. L'Eplattenier, G. Cook, C. Ashcraft, M. Burger, J. Imbert, M. Worswick, Introduction of an electromagnetism module in LS-DYNA for coupled mechanical-thermal-electromagnetic simulations, Steel Research International 80 (2009) 351-358. https://doi.org/10.2374/SRI08SP152

[13] Psyk. V, Prozesskette Krümmen – Elektromagnetisch Komprimieren – Innenhochdruck-umformen für Rohre und profilförmige Bauteile, PhD Thesis, TU-Dortmund, 2009.

[14] Reuther. F, Mosel. A, Freytag. P, Lambarri. J, Degenkolb. L, Werner. M, Winter. S, Numerical and experimental investigations for hot metal gas forming of stainless steel X2CrTiNb18, Procedia Manufacturing 27 (2019) 112-117. https://doi.org/10.1016/j.promfg.2018.12.052