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Innovative joining methods for lightweight designs, Part II*

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Joining by hydroforming and electromagnetic expansion

Methods and procedures: The complexity of the lightweight nodes and their requirements of geometric accuracy and surface quality need precise process planning and adequate machining set-up for manufacturing. Multi-axis machining set-ups provide a high flexibility in development and realisation. They allow milling, drilling, threading and reaming of the nodes from five sides, depending on the machining system being used. The decrease in the number of changes to the clamping set-up avoids interactive defects and geometric inaccuracies and therefore increases the economic efficiency of the process.

From a given CAD model of the frame structure with all the necessary elements, the models of the nodes can be used for further planning (Fig. 1). The CAM system, as used for the manufacturing of complex parts like dies and moulds, allows the generation of machine specific NC data, depending on which element or surface should be manufactured and which tools and cutting parameters should be used. A Deckel-Maho 5-axis milling and machining centre (DMU 50 Evolution) was chosen to manufacture the lightweight node and its integrated structured surfaces.

There are two basic ways to structure the surface of a joining zone. The micro structure can be described by characteristic surface parameters, e.g. average surface roughness, core roughness depth, or the contact area percentage. This is important for a tight fit between the inner and the outer specimen [20]. Macrostructures can be seen as pockets, grooves and nuts, which allow the profile to fit into or onto the node to obtain a form-fit. The transition between both types of surface characteristics is smooth, with the definition within this article being that macro structures have a visible depth (> 50 µm) and micro structures are only measurable (< 50 µm) but not visible. The micro structured surfaces lead to a more interference-fit-based connection due to the influence of the friction and tangential stresses between both joined elements. Macrostructured surfaces allow a form-fit joint.

It must be taken into account, however, that the degree of deformation depends on both the material characteristics and the shape (depth, width, length) of the formed element. For the purpose of process-safe, economic, and flexible milling, coated standard ball end mills aluminium were chosen to mill the aluminium. Helical tool paths for the simultaneous five-axis finishing strategies help to keep constant engagement conditions between tool and work piece in order to produce a homogeneous, constant →

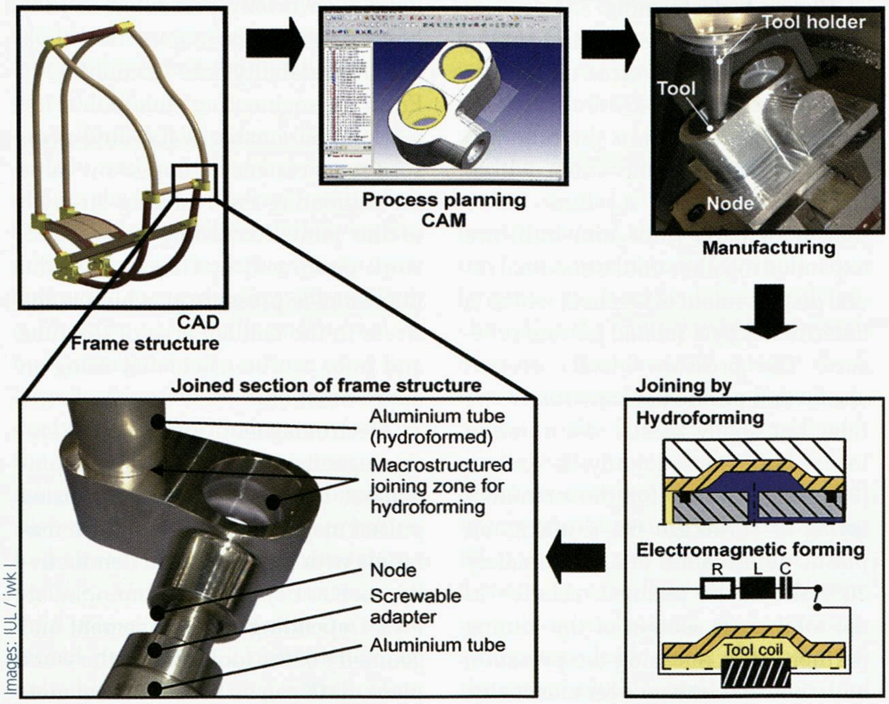


Fig. 1: Process chain for joining of frame structures

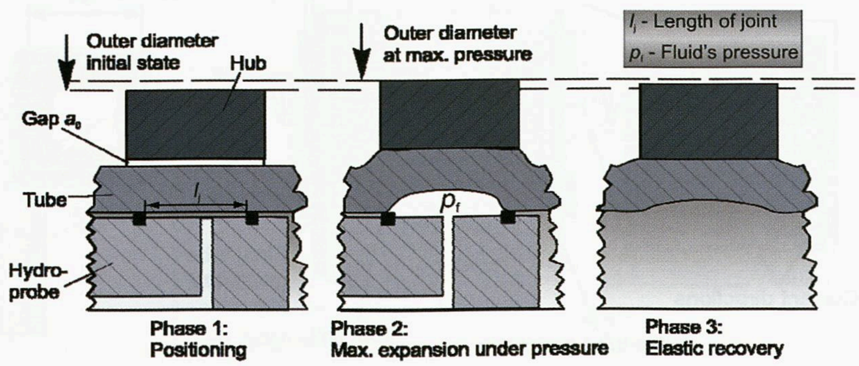


Fig. 2: Process of joining by dieless hydroforming

* *Part I of this paper, focusing on friction stir welding and bifocal hybrid laser welding, was published in ALUMINIUM 1-2/2010.*

surface quality, to avoid collisions between the tool and the tool holder and to reduce the risk of long, oscillating tools [Wei05]. After production has taken place, one of the forming processes can be used to assemble the frame components.

Dieless hydroforming: The process of joining by dieless hydroforming can be divided into three characteristic phases, which are indicated in Fig. 2. In the first phase, the tube will be expanded to some value within the clearance (gap a_0) limit. After that, both parts (tube and hub) are expanded together until a maximal radial displacement is reached, which is determined by a related joining pressure. The pressure ideally creates elastic and plastic deformation in the tube but solely elastic deformation in the hub. Consequently, Kollmann [21] suggests that for the manufacturing of shrinkage fits a maximum plastic deformation of approximately 30% should be attained, relative to the total cross section of the joining partner. After releasing the pressure, both tube and hub recover elastically. Subsequently, the elastic recovery of the hub is prevented due to the plastic deformation remaining in the expanded tube.

Furthermore, the prevented elastic recovery of the hub results in an interference fit between the joining partners (tube and hub). It is known from the manufacturing of camshafts that if both joint partners possess the same Young's modulus then the joining partners should be arranged with increasing yield points from the inner to the outer joining partner [22]. Joining of aluminium and magnesium, as well as the influence of maximum expansion under pressure, wall thickness of the hub, and initial gap on the strength of the joint, have been briefly presented in [23]. More detailed discussions take tools and repeatability into account [24]. From an engineering standpoint, the working parameter of the fluid pressure p_f represents an important value for estimating the resulting strength of the joint. According to research work performed by Garzke [22], the interference pressure *p*, which is the stress in the contact area of the tube and hub, can be calculated using an approximation.

Electromagnetic expansion: Electromagnetic forming (EMF) is a non-contact high velocity process using pulsed magnetic fields to deform materials with high electrical conductivity, such as copper and aluminium alloys. Depending on arrangement and geometry of the tool coil and the work piece, EMF can be used for sheet metal forming operations or for compression or expansion of hollow profiles [25]. Fig. 3 shows the typical set-up of work piece, tool coil and forming machine for the electromagnetic expansion of a square tube. This set-up can be represented by a resonance circuit in the equivalent circuit diagram. Within this diagram the forming machine is symbolised by the capacitance *C*, the inner resistance R_i and the inner inductance L_i. The work piece and the tool coil can be seen as the consumer load. Due to a sudden discharge of electricity from the capacitor, a damped sinusoidal current *I(t)* runs through the coil. This current, which typically ranges from 10 to 1,000 kA, generates a magnetic field *H(r,z,t)* around the coil within several microseconds. According to Lenz's law, this magnetic field induces eddy currents in the work piece which are in the opposite direction of the coil current, and shield the magnetic field. The energy density of the magnetic field represents a pressure *p(z,t)* acting orthogonally on the workpiece [25]. Plastic deformation of the tube will occur once the stresses in the work piece due to this pressure exceed the yield stress of the material.

A currently well investigated application of EMF in research is the forming of sheet metal where the work piece can either be deformed freely or into a die to create a defined shape. The process can also be used to calibrate work pieces which were preformed by a conventional quasi-static process [26] or for cutting/shearing operations, but the most commonly used industrial application of EMF is the joining of closed hollow profiles. By using electromagnetic compression or expansion it is possible to produce dominating interference-fit joints or dominating form-fit joints [27]. In the case of very high impact velocities of the electromagnetically driven part it is possible to produce adhesive bonds between the joining partners. This application is called magnetic pulse welding [28]. The strength of the interference-fit depends on the area of the contact zone, the friction coefficient and the residual interference stresses in the contact zone. The interference stresses are influenced by the material properties of the joining partners, such as yield stress and Young's modulus. The geometrical stiffness of the part to be joined also affects the interference stresses [29]. According to [30] and [31] the strength of interference-fit joint produced by electromagnetic compression depends on the geometry and the shape of the groove as well as on the number of grooves. Both authors

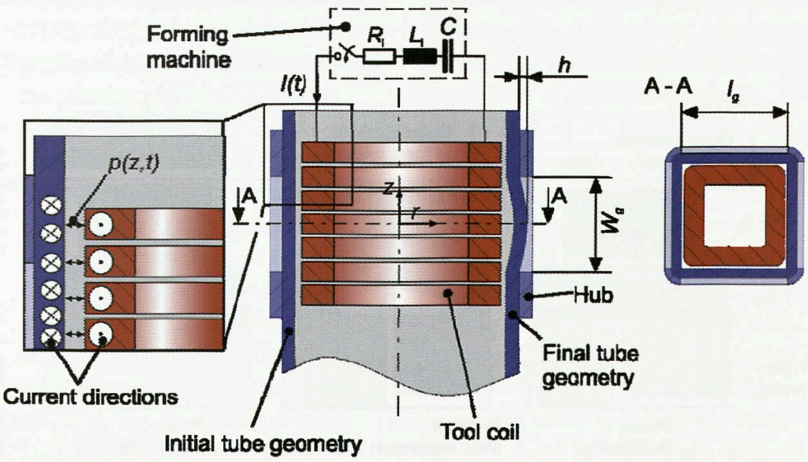


Fig. 3: Principle of the production of a square tube-to-hub joint by electromagnetic expansion

used cylindrical specimens for their analyses.

Analysis of joint characteristics

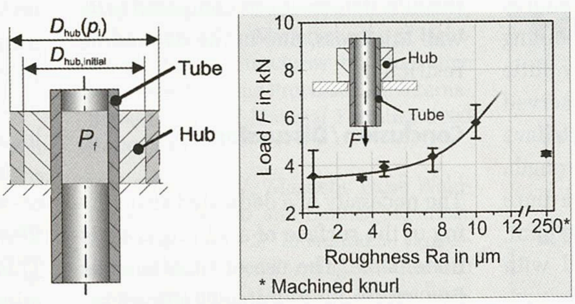
Strength of hydroformed joints: The strength of the joint against an axial load is mostlydependent on the area of contact A_{con}, the interference pressure p, and the friction coefficient μ between the two joining partners, as indicated in equation (1)

$$F_{ax} = A_{con} \cdot \mu \cdot p \qquad (1)$$

The area of contact A_{con} depends on the length of the joint l_j as well as the interference diameter, and is directly proportional to the resulting axial load F_{ax}. However, the interference pressure depends on the inner and outer diameter of joining partners, material characteristics as yield stress, Young's modulus, and Poisson's ratio, and the maximum fluid pressure during joining. Joining of two tubes made from the same material results in a low maximum axial load [27]. As a result, for an appropriate axial load to be achieved, a modification of the coefficient of friction seems reasonable. Therefore, adequate manufacturing strategies, developed by the ISF, to specifically adjust the roughness of the tube have been applied and its results on the strength of the joint have been investigated. In addition to the surface finishing by machining, burnishing was also applied as a forming process for surface finishing. The mean roughnesses achieved by the mentioned processes were R_a = 0,63 μm by burnishing, R_a = 3,4 μm to R_a = 7,5 μm by milling [32] and R_a = 10 μm by turning. To generate a disproportionately high roughness a knurl pattern was applied to the surface by a milling process, so that a calculated roughness of R_a = 250 μm as found. Tubes prepared so far were made from aluminium EN AW-6060, with an outer diameter of 40 mm and a wall thickness of 2 mm. They were joined with ring-shaped hubs that had an outer diameter of 50 mm and a wall thickness of 5 mm. Taking the results of preliminary investigations [33] into account an acceptable tangential strain of approximately 1.5% was detected, and the gap a_0 was set to 0 mm. The pressure in phase 2 was adjusted to 74 MPa, resulting in an expansion of 0.4 mm. After joining, an axial load was applied using a tensile test machine, and the results are displayed in Fig. 4.

At first, an increase of the average surface roughness led to an increase of the axial load. Tubes with a knurled surface were significantly less resistant to deformation during tensile tests compared to specimens with a milled surface. As a result, the peaks created by knurling the tube surface were too large to generate an appropriate undercut with the opposite surface of the hub. Moreover, a penetration of the roughness peaks into the opposite surface did not occur as the pressure had already led to the maximum expansion. Using a die, an increase of fluid pressure could lead to the mentioned penetration. Consequently, as only the tips of knurling were in contact to the inner surface of the hub, the area of contact was significantly smaller compared to the machined specimens. Since the area of contact is directly proportional to the axial load, the reduction in maximum axial load is clearly evident.

Joining of square reinforced aluminium profiles by electromagnetic expansion: Previous analysis regarding the strength of form-fit joints considered primarily tubular specimens deformed by electromagnetic compression [30, 31]. This work is a first experimental approach to extend these analyses of form-fit joints towards reinforced square tubes produced by electromagnetic expansion. To generate the form-fit joints a specified area of the tube was expanded into the grooves of the outer joining partner, the hub (see Fig. 3). The square tool coil used within these experiments has an edge length of 40 mm and a length of 30 mm with 8 turns (E-40sqr-8/30). For this first approach the groove width w_g and the groove length l_g were kept constant. For w_g a value of 20 mm was chosen, which equals four times the wall thickness of the profiles. For the magnitude of l_g the inner diameter of the tubes was chosen (40 mm). The height of the buckles h was varied by changing the acting magnetic pressure and the charging energy E of the capacitor bank. The maximum height of the buckles was restricted by the beginning of debonding at the interface between the reinforcement wire and aluminium matrix. During the expansion of the tube the reinforcement wires are elongated. Due to volume constancy an increasing elongation leads to a decrease of the cross section and, therefore, to a separation of matrix material and wires [29]. Debonding at the interface disables or reduces load transmission between matrix and wire, and therefore is not acceptable. To determine the maximum allowable deformation and the corresponding charging energy for the joining, a preliminary test series was performed whereby the profiles were expanded with different charging energies within a defined area and restricted by solid collars. The distance between collars was equivalent to the groove width w_g. The set-up of the preliminary experiments is shown in Fig. 5. After the deformation the heights →



Tube	EN AW-6060	
Wall thickness:	S_{tube}	= 2 mm
Outerdiameter of the tube :	D_{tube}	= 40 mm
Hub	EN AW-6060	
Wall thickness:	S_{hub}	= 5 mm
Outerdiameter of the hub:	$D_{hub,initial}$	= 50 mm
$D_{hub}(p_i)$-$D_{hub,initial}$		=0.4 mm

Fig. 4: Axial load depending on the surface finish of joints made by dieless hydroforming

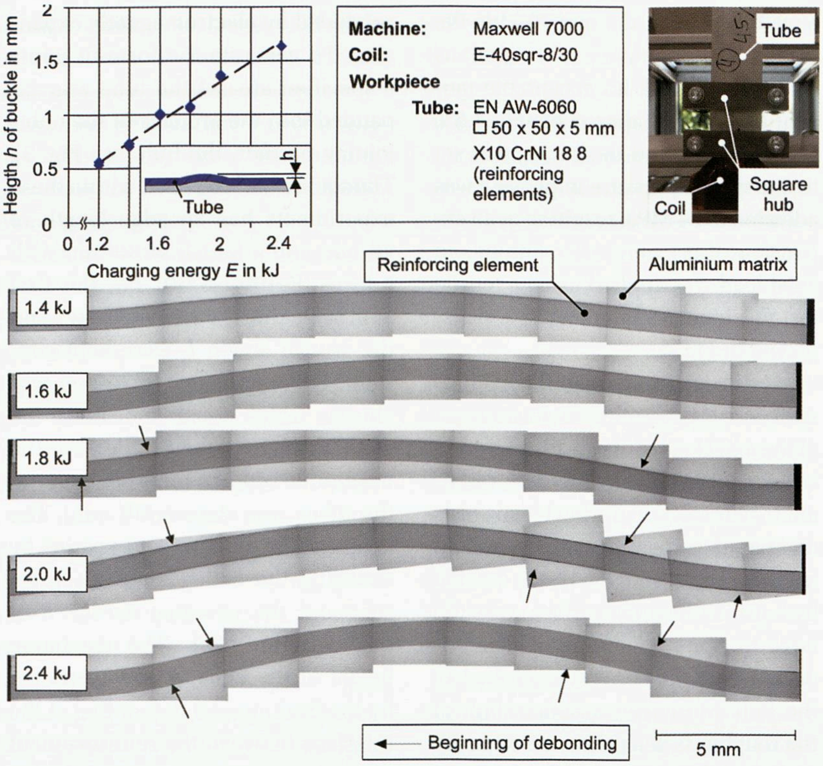


Fig. 5: Top: Set-up and results of the preliminary tests for the expansion of reinforced square tubes; bottom: Micrographs of the expanded tubes parallel to the wire

of the resulting buckles were measured with a coordinate-measuring machine. The results show that an increase in charging energy leads to an increase in deformation.

In order to evaluate the quality of the bonding between the aluminium matrix and the reinforcement elements, micrographs of the electromagnetically formed specimens were prepared, which also clearly show the increasing deformation of the tube with increasing charging energy. Charging energies of up to 1.6 kJ did not result in debonding at the interface between the matrix material and the wire. A further increase of the charging energy led to debonding at the interface, marked with arrows in Fig. 5. Based on these preliminary tests, a maximum charging energy of 1.8 kJ was chosen for the joining experiments. Although a very little amount of debonding was observed at this energy, it was assumed to have no influence on the material strength. To separate the influence of a pure form-fit from the strength of the joint, all specimens were lubricated with Teflon grease before joining. As a result, the friction coefficient between the joining partners was lowered to a negligible level. Therefore, it was possible to nearly prevent an additional interference-fit in the areas surrounding the grooves. After preparation the specimens were expanded into the grooves of the hub. Charging energies of 1.2 kJ, 1.4 kJ and 1.8 kJ were used. Afterwards, pullout tests of the joints were conducted using a universal tensile testing machine. The experimental results are shown in Fig. 6. The diagram of the pullout force F with respect to E indicates that a higher charging energy and the resulting larger height of the buckles lead to a higher strength of the joint. It can also be seen that the strength of the almost pure form-fit is very low compared to the material strength. This can be explained by the small ratio of the tube deformations compared to its wall thickness, due to the debonding restriction.

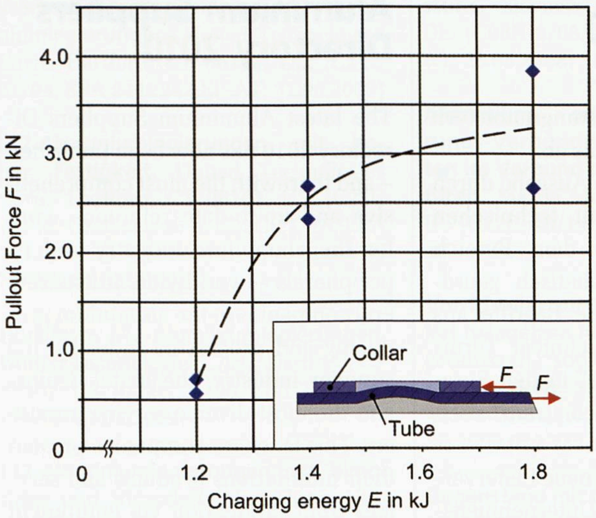
Conclusion / Discussion

The necessity of a dedicated structuring of the surface of a joining zone is undeniable. The use of simultaneous five-axis milling strategies allow a reproducible structuring of the surface of lightweight connecting elements in order to control and increase tensile and torsional strength of a joint. Interference-fit joining by expansion of joining partners made from equal material results in a weak interference pressure. As a result, the strength of the joint determined by the area of contact, interference pressure and the coefficient of friction can be increased by modifying the surface structure. Consequently, experimental investigations conducted so far have confirmed the possibility of increasing the strength of the joint by increasing the average surface roughness. However, there is a limit to the increase in strength which can be achieved by increasing the roughness. The joining experiments of reinforced square aluminium tubes by electromagnetic forming showed that an increase in the height of the buckles leads to an increase in the strength of the joint. It was also shown that the resulting joint strength was low within these tests due to the small allowable deformation. To achieve reasonable strengths of the joints, a combination of an interference-fit and form-fit would be better. Also, an optimisation of the form-fit might be helpful to increase the transferable load. In the case of non-reinforced tubes it can be assumed that significantly higher joint strengths can be achieved, since larger deformations are feasible. Hence, the knowledge of the interrelation between specific surfaces and the resulting effects on the quality of the joint allows the configuration of a flexible process chain for machining and joining lightweight frame structures.

Conclusions

The presented innovative joining methods allow for flexible manufacturing of lightweight frame structures in limited-lot production. They enable an economic production process and lead to a lower structure weight.

Experiments show the weldability of steel reinforced aluminium profiles by using friction stir welding. This method is able to join the aluminium matrix material, but does not connect the reinforcing elements. The pre-treatment (sawing, milling) of the



Machine: Maxwell 7000
Coil: E-40sqr-8/30
Workpiece
Collar: EN AW-6006A, □ 60 x 60 x 5 mm
Tube: EN AW-6060, □ 50 x 50 x 5 mm, X10 CrNi 18 8 (reinforcing elements)

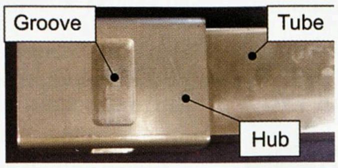


Fig. 6: Results of the pullout tests of square reinforced tubes joined to square hubs

specimen has no significant influence on the joint strength. The aluminium alloy EN AW-6060, which is nearly impossible to fusion weld, can be joined by using bifocal hybrid laser welding. It could be shown that tube-tube-I-joints can be produced with 93% of the tensile strength of the tubes by using an end crater reduction strategy. For modern joining by forming processes an undeniable necessity for dedicated structuring of the surface of the joining zone exist. The knowledge of the interrelation between specific surfaces and the resulting effects on the quality of the joint allows for the configuration of a flexible process chain for machining and joining lightweight frame structures.

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References

References from [1] to [19] are listed in Part I of this paper, see ALUMINIUM 1-2/2010.

[20] Hammers, T.; Marré, M.; Rautenberg, J.; Barreiro, P.; Schulze, V.; Löhe, D.; Brosius, A.; Tekkaya, E.: Influence of mandrel's surface on the mechanical properties of joints produced by electromagnetic compression. In: ICHSF 2008 – 3rd International Conference on High Speed Forming, 11/12 March 2008, Dortmund, Germany, Proceedings, pp. 245-256, ISBN 3-9809535-3-X

[21] Kollmann, F.: Welle-Nabe-Verbindungen, Gestaltung, Auslegung, Auswahl, Springer Verlag Berlin (1984)

[22] Garzke, M.: Auslegung innenhochdruckgefügter Pressverbindungen unter Drehmomentbelastung. Dr-Ing. Thesis. TU Clausthal, VDI Verlag Düsseldorf, 2001

[23] Homberg, W.; Marré, M.; Beerwald, C.; Kleiner, M.: Joining by forming of lightweight frame structures, In: Advanced Materials Research: Flexible Manufacture of Lightweight Frame Structures, Band 10 (2006), pp. 89-100

[24] Przybylski, W.; Wojciechowski, J.; Marré, M.; Kleiner, M.: Influence of design characteristics and manufacturing process parameters on the strength of tubular aluminium joints produced by hydroforming. In: Archives of Mechanical Technology and Automation, Vol.27 Nr. 1, Polish Academy of Science, 2007, pp. 152-167 ISSN 1233-9709

[25] Bruno, E. J.: High Velocity Forming of Metals. Dearborn, Michigan: ASTME, 1968

[26] Psyk, V.; Beerwald, C.; Henselek, A.; Homberg, W.; Brosius, A.; Kleiner, M.: Integration of Electromagnetic Calibration into the Deep Drawing Process of an Industrial Demonstrator Part. In: Key Engineering Materials Vol. 344 (2007), pp. 435-442

[27] Marré, M.; Ruhstorfer, M.; Tekkaya, A. E.; Zaeh; M. F.: Manufacturing of Lightweight Frame Structures by Innovative Joining by Forming Processes. In: International Journal of Material Forming, 2009 – accepted

[28] Shribman, V.: Magnetic Pulse Welding for Dissimilar and Similar Materials. In: ICHSF 2008 – 3rd International Conference on High Speed Forming, 11/12 March 2008, Dortmund, Germany, Proceedings, pp. 245 -256, ISBN 3-9809535-3-X

[29] Marré, M.; Brosius, A.; Tekkaya, A. E.: Joining by Compression and Expansion of (Non-) Reinforced Profiles – In: Flexible Manufacture of Lightweight Frame Structures - Phase II: Integration, Weinert, K. et al. (eds.), TTP Trans Tech Publications Ltd, Switzerland, Advanced Materials Research (2008) Vol. 43, ISBN 0-87849-385-9, pp. 57-68

[30] Golovashchenko, S.: "Methodology of Design of Pulsed Electromagnetic Joining of Tubes", Proceedings of the TMS Symposium "Innovations in Processing and Manufacturing of Sheet Materials", 11-15 February 2001, New Orleans, Louisiana, pp. 283-299

[31] Bühler, H.; v. Finkenstein, E.: Bemessung von Sickenverbindungen für ein Fügen durch Magnetumformung. In: Werkstatt und Betrieb Vol. 104 (1971), pp. 45-51

[32] Biermann, D.; Weinert, K.; Zabel, A.; Engbert, T.; Rautenberg, J.: Machining of Lightweight Frame Components. In: Flexible Manufacture of Lightweight Frame Structures – Phase II: Integration, Weinert, K. et al. (eds.), TTP Trans Tech Publications Ltd, Switzerland, Advanced Materials Research (2008) Vol. 43, ISBN 0-87849-385-9, pp. 37-46

[33] Hammers, T.; Marré, M.; Rautenberg, J.; Barreiro, P.; Schulze, V.; Biermann, D.; Brosius A.; Tekkaya, A. E.: Influence of Mandrel's Surface and Material on the Mechanical Properties of Joints Produced by Electromagnetic Compression. steel research int., May Vol. 80 (2009) No. 5, S. 366-375; DOI: 10.2374/SRI08SP151

Appendix

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