Int J Mater Form (2010) Vol. 3 Suppl 1:1031–1034
DOI 10.1007/s12289-010-0946-2

JOINING OF LIGHTWEIGHT FRAME STRUCTURES BY DIE-LESS HYDROFORMING

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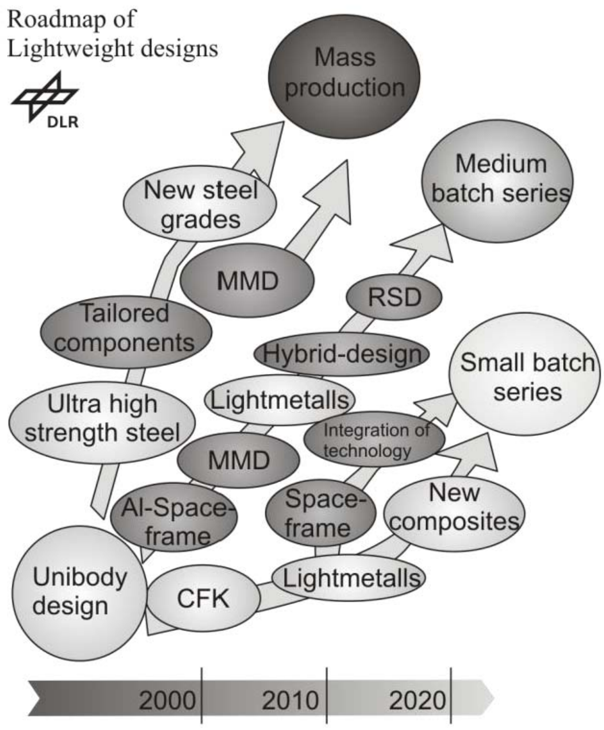
ABSTRACT: A successful approach to achieve a reduction of a car's total weight is the implementation of lightweight strategies in the design process, e.g. using lightweight materials. An interesting alternative to conventional welding and riveting processes is joining by die-less hydroforming. This work describes an analytical model which can be used to calculate the strengths of these joints, taking into account the material parameters, joint geometry and process parameters. Additionally, validation of the model by both finite element simulations and experiments will be provided. Furthermore, investigations were carried out to implement the described methodology for a multi-joint used in a space frame structure.

KEYWORDS: joining by forming, die-less hydroforming, space frame

1 INTRODUCTION

In the context of current debates on climate change and its consequences and the limitation of the natural resources, lightweight concepts are becoming more important. Lightweight materials and related lightweight techniques result in a reduction of the energy and material requirements. In addition to aeronautical engineering, the automotive industry is one of the most important technology driver in this area. Automobiles are significant contributors to the harmful $C0_2$ emissions with a continuous increase in passenger traffic. A long term reduction of CO_2 emissions can only be achieved by using alternative technologies [1]; i.e. e-mobile, in addition to the short term approach of saving fuel through the reduction of the vehicle weight [2]. The vision is the realization of a $C0_2$ neutral vehicle. Solutions for this are intelligent lightweight construction strategies, shown in Figure 1, that give the possibility to reduce the vehicle weight while increasing functionality. Promising approaches are multi-material design and hybrid construction [3].
This is based on the fact that in most cases the load on structure components is not homogeneous. By optimizing the design of the components by partial substitution of materials and local reinforcements in dependence on the required strength and/or stiffness of the parts locally, a significant weight optimization could be realized. By doing this, the expensive light weight material is applied only in the necessary areas. Therefore, the diversity of materials in automobiles will continue to increase [4]. Alternative and new materials will only be economical to use, if an appropriate solution for joining and processing exists [5]. Especially by the application of different materials, thicknesses and properties, conventional joining methods are no longer applicable [6].



MMD Multi material design

RSD Rib and space frame design

Figure 1: Lightweight design [2]

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Either the materials cannot be joined to each other or the heat will cause disadvantages to the joints. In many cases their use is associated with high manufacturing and assembly costs. At the same time, the achievement in weight reduction by the use of lightweight materials should not be burned out by the joining process. Moreover, it is not just about using special technologies and procedures to establish a secure connection, but also to generate a high level of component and group stability. That means it is not only essential to achieve maximum stiffness and stability but also to realize a predefined deformation behaviour. An example of a modern lightweight space frame structure is the BMW-C1E prototype powered by an electric drivetrain, displayed in Figure 2.

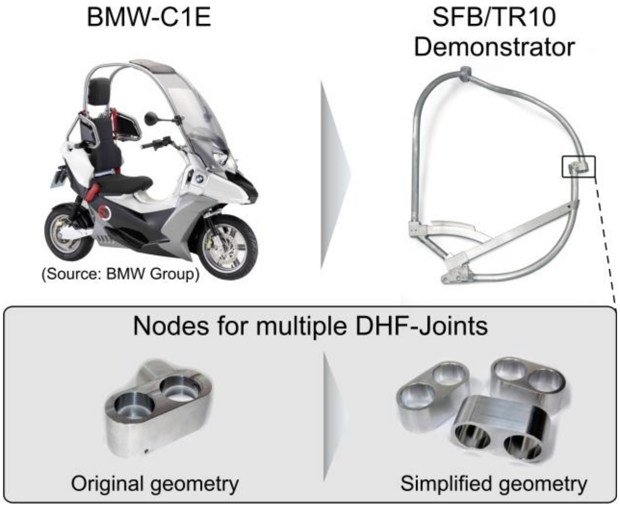

Figure 2: SFB/TR10 Demonstrator Frame [7]

This example was taken as a reference and a demonstrator of the Collaborative Research Center SFB/TR10. The demonstrator's purpose is to show new forming, cutting and joining processes developed and investigated within the SFB/TR10 [8]. One example of the joining processes is the joining by die-less hydroforming (DHF), also known as hydraulic expansion. Manufacturing of heat exchangers, camshafts, intermediate shafts or cylinder liners is done using DHF nowadays [9]. Furthermore, this joining process is potentially suitable for joining extruded profiles to cast or machined nodes. Basically, the joining partners have to be aligned in a typical shaft-to-collar-configuration [10]. In Figure 2, the lower section shows a machined node and its accordingly simplified geometry, which was used for the experimental studies.

2 INTERFERENCE PRESSURE

To initiate the joining process, a joining tool, introducing it as hydro-probe, is positioned inside the tube and axially underneath the other joining partner. In a gap between hydro-probe and tube, a pressurized fluid (water, hydraulic media etc.) is applied. If the pressure, which acts locally in the joining area because of a limitation in axial direction by sealings, exceeds the tube's yield strength, plastic deformation of the tube occurs [11]. The main parameters for describing the DHF process are listed in Table 1 and are taking into account material parameters, the geometry of both joining partners and the process parameter.

***Table 1:** Parameters in DHF*

Parameter	Description
Index I	Inner joining partner
Index O	Outer Joining Partner
p_i	Fluid pressure
$k_{f,}$	Yield stress
E	Young´s modulus
Q	Ratio of diameter: inner to outer
υ	Poisson's ratio

The final strength of a joint against an axial force F_{ax}, where μ is the coefficient of friction, A_{con} is the area of contact loaded by the interference pressure p and l_j represents the length of the joint interface, is defined as

$$F_{ax} = A_{con} \cdot \mu \cdot p = d \cdot \pi \cdot l_j \cdot \mu \cdot p \tag{1}$$

An analytical model was developed by Garzke [12] to calculate the interference pressure between a thick walled tube and a ring after joining. As Figure 3 indicates, there are four significant strains, each related to the interference diameter.

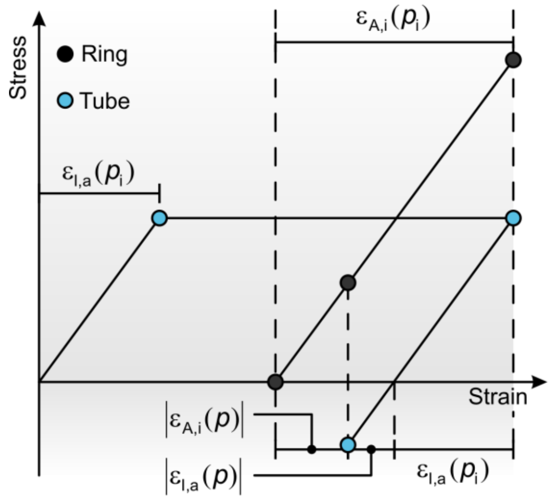

Figure 3: Stress and strain in DHF [4]

These four strains are defined as:

- $\varepsilon_{I,o}(p_i)$ as the elastic expansion of the tube under fluid's pressure,
- $\varepsilon_{O,i}(p_i)$ as the elastic expansion of the ring under internal pressure,
- $\varepsilon_{I,o}(p)$ as the elastic expansion of the tube under interference pressure and finally
- $\varepsilon_{O,i}(p)$ as the elastic expansion of the ring under interference pressure.

The strains can be summed up in Equation 2 as:

$$\varepsilon_{O,i}(p_i) = \varepsilon_{I,a}(p_i) + |\varepsilon_{I,a}(p)| + |\varepsilon_{O,i}(p)| \qquad (2)$$

Assumed were plain stress, elastic and ideal plastic as well as isotropic material behavior. The interference diameter d is defined as equal to the outer diameter d_O of the inner joining partner (tube) and the inner diameter d_I of the outer joining partner (ring). Equation 1 can be solved taking TRESCA's flow rule and LAMÉ equations into account. This leads to an interference pressure p displayed in Equation 2. Determination of the interference pressure p is executable, taking material and process parameters into account. Verification of Equation 2 has been done using the commercial FE program Ansys 11.

$$p = \frac{\dfrac{p_i - k_{f,I}\cdot\ln\dfrac{1}{Q_I}}{E_O}\left(\dfrac{1+Q_O^2}{1-Q_O^2}+\nu_O\right)+\dfrac{2\cdot Q_I^2\cdot k_{f,I}\cdot\ln Q_I}{E_I\cdot\left(1-Q_I^2\right)}}{\dfrac{1}{E_O}\left(\dfrac{1+Q_O^2}{1-Q_O^2}+\nu_O\right)+\dfrac{1}{E_I}\left(\dfrac{1+Q_I^2}{1-Q_I^2}+\nu_I\right)} \qquad (3)$$

A comparison between Equation 2 and the FE results is displayed in Figure 4 for the aluminum alloy EN AW-6060.

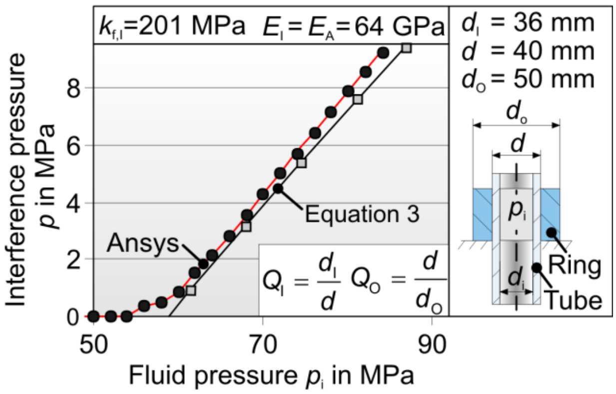

Figure 4: Calculation of interference pressure

3 MULTIPLE DHF JOINTS IN SPACEFRAMES STRUCTERS

The basic mechanical challenge in the application of DHF in the manufacturing of lightweight frame structures is predicting the strength of the joint. The analytical model described above is valid for the joining of two tubes and does not take into account any side effects caused by a more complex geometry of the node. Consequently, adopting the model begins with defining a proper geometry by assuming a substitute diameter of the outer joining partner. A substitute diameter d_O representing the effective outer diameter of the node has been introduced. Therefore, the necessary ratio of diameter Q_O and the according interference pressure p can be calculated. This substitute diameter is defined as $d_O = d + s_{min}$ whereas s_{min} is the minimal wall thickness of the drill hole, as indicated in Figure 5. The substitute diameter, is independent of the bridge thickness, which is the distance between the two drill s_{min}. To verify this substitute diameter, model investigations were done by joining one and two tubes into three types of nodes with different bridge thicknesses s_{bridge}. After joining, the specimens were tested on a tensile test machine. The resulting strength of the joint against an axial force F_{ax} was used to calculate the interference pressure $p_{experimental}$ according to Equation (1).

To evaluate the quality of the substitute diameter, the experimentally determined interference pressure was normalized to the analytic interference pressure, which was calculated using Equation (3) taking the substitute diameter into account. A ratio of 1.0 indicates no deviation between the experimental and analytic values and verifies the substitute diameter model. The results of these investigations are shown in Figure 5.

If just one tube is joined into the node, the corresponding specific interference pressure shows a linear dependency on the bridge thickness, which can be attributed to a higher stiffness of the node.

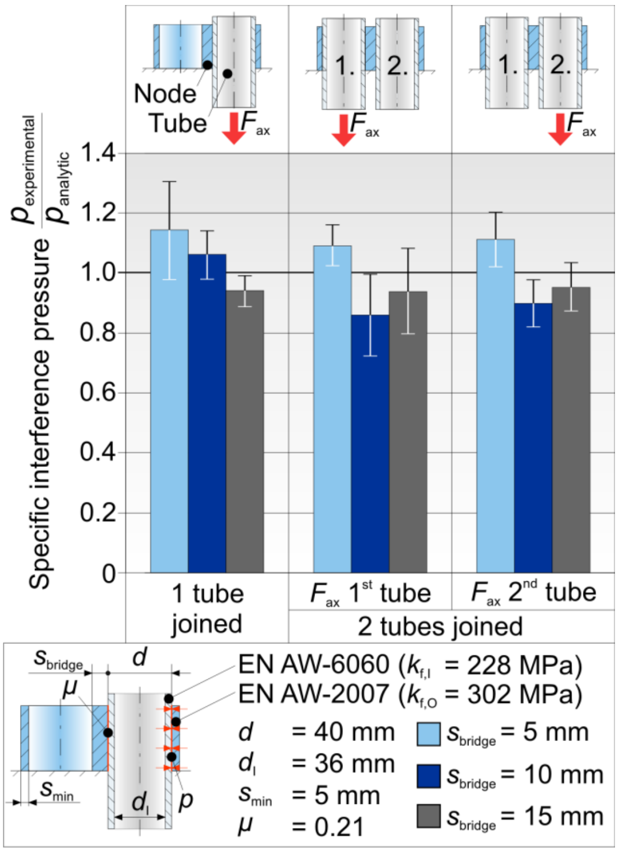

Figure 5: Specific interference pressure

Nevertheless all joints take values between 1.14 and 0.94 so that the substitute diameter can be seen as an adequate approximation for the effective outer diameter of the node. In the second step, two tubes were successively joined into the node to identify interactions between the two joints and side effects on the strength of the joint. Figure 5 indicates that there is no significant influence in the specific interference pressure for two successively joined tubes, taking a bridge thickness of s_{bridge}=5mm and (s_{bridge}=15mm) into account. However, with node type 2 (s_{bridge}=10mm) a significant decrease of the specific interference pressure was observed. As a result, interactions between the two joints depend on the bridge thicknesses in a non-linear way. The reason for this non-linearity can be explained as a kind of leverage effect, in which the bridge between the two drill holes acts as a pivotal point, indicated in Figure 6. As a consequence, the radial expansion of the node during the joining process of one tube initiates a subsequent backward deformation of the second joint and leads to a decrease of strength. In case of a bridge thickness of s_{bridge} = 15 mm, the leverage effect is insignificant because of the large distance between the two joints. In case of a bridge thickness of s_{bridge} = 5 mm, the bridge can not work as a pivotal point as the bridge is plastically deformed.

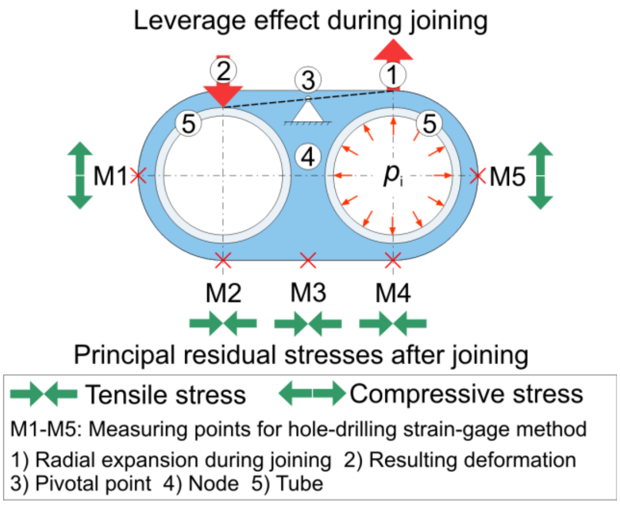

Figure 6: Leverage effect

As a result, there are no significant differences in the specific interference pressures of the primarily joined tube and the subsequently joined tube, which proves that the order of joining does not influence the strength of the joint.

4 CONCLUSIONS

An analytical model to determine the interference pressure between the joining partners has been applied in the joining of nodes of a space frame structure. Consequently, validation of the model could be proved be simulation and experiments. Furthermore, the influence on the strength of the joint by the joining sequence has been investigated. As a result, taking the suggested methodology of designing a feasible bridge thickness into account, the joint's strength is independent of the joining sequence.

ACKNOWLEDGEMENT

This paper is based on investigations of the Collaborative Research Center SFB/TR10 which is kindly supported by the German Research Foundation (DFG).

REFERENCES

[1] Goubeau A.: Der Mini E – Ein Beispiel für $C0_2$ freies Autofahren? 4. Dortmunder Autotag, Dortmund, 2. September 2009.

[2] Piller A., Friedrich H. E., Kopp G., Henning F.: Fügen von faserverstärkten Kunststoffen in Multi-Material-Fahrzeugstrukturen aktuelle Forschungs-ergebnisse. 11. Internationale AVK-Tagung, 22.-23. September 2008, Essen, Deutschland.

[3] Contornoa D., Filiceb L., Fratinia L., Micaria F.: Forming of aluminum foam sandwich panels: Numerical simulations and experimental tests. Journal of Materials Processing Technology Volume 177, Issues 1-3, 3 July 2006, pages 364-367, In: Proceedings of the 11th International Conference on Metal Forming, 2006.

[4] Tröster Th., Lauter Chr.: Leichtbau mit höchstfesten Kunststoff-Metall-Hybriden. Vortrag im Rahmen der Veranstaltungsreihe „Hochschule trifft Mittelstand vor Ort", Meinerzhagen, 16. 09. 2009.

[5] Geiger M., Micari F., Merklein M., Fratini L., Contorno D., Giera A., Staud D.: Friction Stir Knead Welding of steel aluminium butt joints. International Journal of Machine Tools and Manufacture, 48(5):515-521, 2008.

[6] Borsellino C., Buffa G., Fratini L., Ruisi V.F.: Technological alternatives in the joining of lightweight aluminum structures. Image Processing, Biomedicine, Multimedia, Financial Engineering and Manufacturing - Proceedings of the 6th Biannual World Automation Congress, pp. 401-406.

[7] Munzinger C., Lanza G., Elser J., Ruch D., Schneider M., Köhler G., Gerbracht T., Ochs A., Marré M., Becker D., Selvaggio A., Huber S., Ruhstorfer M.: Prozesskette zur flexiblen Herstellung leichter Tragwerkstrukturen. In: ZWF - Zeitschrift für wirtschaftlichen Fabrikbetrieb, Jahrgang 104, Heft/Band 6/2009, pages 442-449, Carl Hanser Verlag, München, 2009.

[8] Marré M., Brosius A., Tekkaya A. E.: New Aspects of Joining by Compression and Expansion of Tubular Workpieces. International Journal of Material Forming, 1(1):1295-1298, Springer Paris, DOI 10.1007/s12289-008-0140-y, 2008.

[9] Marré M.: Grundlagen der Prozessgestaltung für das Fügen durch Weiten mit Innenhochdruck. Diss. TU Dortmund, Shaker Verlag, Aachen, 2009, ISBN: 978-3-8322-8361-2.

[10] Marré M., Ruhstorfer M., Tekkaya A.E., Zaeh M.F.: Manufacturing of lightweight frame structures by innovative joining by forming processes, Int. Journal of Material Forming, 2(1):307-310, DOI: 10.1007/s12289-009-0524-7, 2009.

[11] Yokell S.: A working guide to shell-and-tube heat exchangers. McGraw-Hill, New York, USA, ISBN 0-07-072281-1, 1990.

[12] Garzke M.: Auslegung innenhochdruckgefügter Pressverbindungen unter Drehmomentbelastung. Diss. TU Clausthal, VDI Verlag Düsseldorf, 2001.