Hydrojoining

R. Neugebauer[1], R. Mauermann[1], R. Grützner[1]

[1]Fraunhofer-Institut für Werkzeugmaschinen und Umformtechnik IWU,
Reichenhainer Straße 88
09126 Chemnitz
Germany
URL: www.iwu.fraunhofer.de *Co-author-email: reinhard.mauermann@iwu.fraunhofer.de*

ABSTRACT: Manufacturing of complex tube-workpieces often requires medium-based forming processes. Because of the inaccessibility to the inside of the parts, joining of attached parts is difficult. Additional part handling and process steps are necessary. A loss of the high accuracy of hydroformed parts is disadvantageous especially by shape distortion during thermal joining. One solution is the integration of the joining operation into the hydroforming-process. A new integration method is a combination of hydroforming and spot-joining. Spot joining means a version of joining by forming like clinching or self-pierce riveting or fluid molding of functional elements, e.g. with inside or outside thread. The high pressure fluid takes over the task of the die during hydrojoining. This integrated die-less procedure also increases the range of possibilities which are not available with standard techniques. The potential and limits of these new hydrojoining-methods are compared with alternative procedures.

Key words: joining by forming, hydroforming, spot joining, clinching, self-pierce riveting, process integration

1 INTRODUCTION

Joining technology for hydroformed tube-workpieces is often the weak point. Thermal procedures are problematical, because of low fatigue strength and corrosion resistance as well as the loss of accuracy by thermal deformation. Joints of different materials, e.g. aluminium and steel, are realisable in thermal way only in special cases. The use of joining by forming is difficult because normally double-sided access is necessary. Joining after hydroforming always means an additional process step. A solution is the integration of joining operations into the process of hydroforming. The utilization of the fluid as an active component is the basis for the development of two procedures described in this paper.

2 PROCEDURE DESCRIBTION

The first procedure shall be called **Hydro-Self-Pierce Riveting**. The forming fluid is used as a die replacement (figure 1). Step A: The hydroformed sheet (5) and the part to be attached (4) are brought in contact to the hydro forming tool (2) by the fluid (6). Step B to C: The punch (1) presses the spreading rivet (3) into the sheets. The high pressure fluid (6) is preventing too strong bending of the hydroformed sheet (5). To the axial movement of the punch a wobble movement can be overlaid in order to decrease the necessary joining force [1] and thus limit the necessary pressure of the fluid.

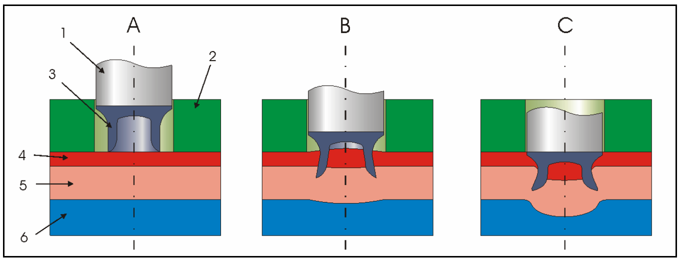

Fig. 1. Operational sequence of the Hydro-Self-Pierce Riveting

The second procedure described is the **Hydro-Clinching**. In this case the fluid works as a punch replacement. Fig. 2 shows the operational sequence.

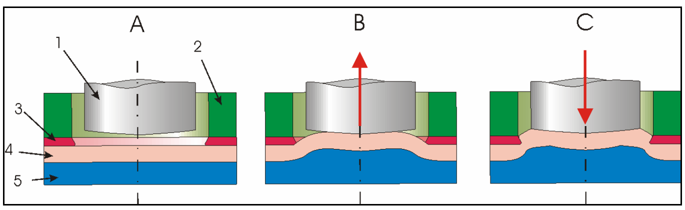

Fig. 2. Operational sequence of the Hydro-Clinching

Step A: The hydroformed sheet (4) and the part to be attached (3) are brought in contact to the hydro forming tool (2) by the fluid (5). Step B: During calibration the hydroformed sheet (4) is pressed through a hole in the part to be attached (3). The punch (1) is withdrawn, in order to avoid bursting and to ensure a higher forming level at the produced bulb. Step C: Subsequently, the punch is set towards the high pressure fluid. Because the back forming is prevented by the high pressure fluid, the material that has been pressed through the hole is spread and develops an interlock. There is also the option of joining without active punch movement. Supported by the hole chamfering of the part to be attached (3), the interlock forms automatically when the bulb is pushed through the hole.

3 FE MODELLING

A similar strategy to the one used for the simulation of massive forming processes was applied to the modelling of the hydro-joining procedures due to the geometrical proportion of the rivet with respect to the sheet metal. The high local deformations lead to strong mesh deformations and require an automatic remeshing algorithm. For this reason the numerical simulations were made with the software DEFORM. A simplified 2 D model with rotationally symmetric four-knot square elements could be built after the characterisation of the boundary conditions (fig. 3).

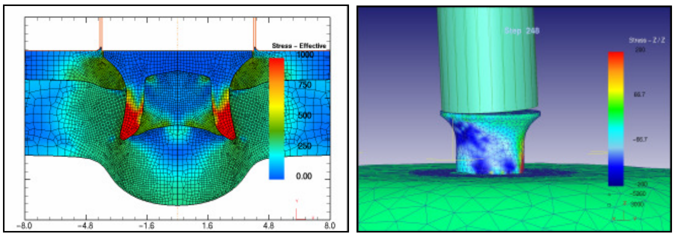

Fig. 3. left: 2D-Effective stress distribution at the end of the joining procedure Hydro-Self-Pierce Riveting, right: 3D-Axial tension distribution during the wobble movement of the punch

In order to simulate crack growth in the riveting procedure, a damage criterion is necessary. Cockroft & Latham offered a criteria based on a macro-mechanical integral damage value which usually gives good results in the case of material cutting [2]. This damage value is calculated from maximum principal stress and effective strain.

The crack growth is implemented in the simulation by the simple elimination of the elements damaged beyond a given threshold value, followed by a remeshing. A characteristic difference of Hydro-Self-Pierce Riveting with respect to self-pierce riveting is that due to the absence of a die there exists a different stress condition in the upper sheet metal on the verge of the material separation. As a function of the fluid pressure, the yield stress and the geometry of the rivet foot, compression stresses at the foot of the rivet are superposed in all directions. For this reason at the rivet foot, the actual place of the material separation, the damage value has an uncritical size. The damage value is much higher in the vicinity of the rivet shaft (left side of figure 4).

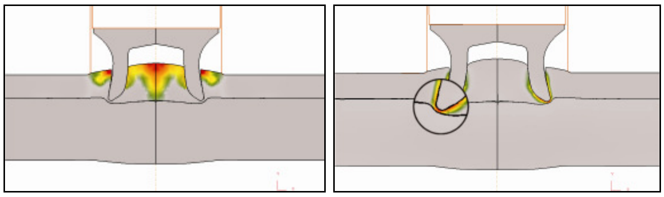

Fig. 4. Damage value distribution at the material separation (left: by Cockroft & Latham; right: by Frobin)

A more suitable separation criterion can be used. It was first proposed by Frobin [3] and it describes the limiting strain φ_B in relation to the state of stress:

$$\varphi_B = \varphi_{BT} \cdot e^{-b\frac{\sigma_m}{\sigma_V}} \tag{2}$$

The variables φ_{BT} and b are material indicators. If the effective strain φ_V attains the limiting strain, the material breaks (right side of figure 4):

$$\int^{\varphi_V} \frac{d\varphi_V}{\varphi_B} = 1 \tag{3}$$

The numerical modelling of the partial joining by forming through wobble movement requires a three-dimensional mesh of volume elements (see figure 3). However due to contact problems during wobbling this kind of simulation requires very long calculation times and strong model simplifications.

4 EXPERIMENTAL TEST

As a test for the practicability of both procedures an experimental tool was designed and built. The tool is designed for fluid pressures up to 2500 bar. The tests were realized for aluminium materials AlMg3, AlMg4.5Mn, Ecodal 608 and AlMg0.7Si alloys of 2-4 mm as well as steel sheets ZStE180BH, DC04 and ZStE260BH of 1.4 mm thickness. The process variables were changed systematically for each set of materials till the case of failure, so that their operational limits were identified. The parameter dispersion contains the geometrical influences of the sheet metals (thicknesses) and of the rivet (length, wall thickness, foot chamfer) on the one hand, on the other hand the material characteristics (yield stress, deformability, hardness) as well as the process parameters (internal pressure, punch movement, joining duration).

5 RESULTS

5.1 Hydro-Self-Pierce Riveting

In the first experiments of the Hydro-Self-Pierce Riveting procedure with prepunched aluminium parts to be attached, joints could be realized with an internal pressure by 600 bar with wobble movement. However it is to be stated that it was impossible to make joints with standard rivets. With these rivets a perforation of the joining partners, with only a slight or without any spreading of the rivets, was observed. In the next experiments the parameter window was determined for a joint without pre-punched hole in the part to be attached. Due to bending crack susceptibility and the limited forming ability of aluminium with respect to steel the parameter window for joining aluminium is small and presupposes a hydroformed part with a minimum thickness of 3 mm. For steel, depending on the sheet metal strength and thickness, the sheets are deformed towards the interior of the rivet starting at a fluid pressure of 1200 bar. Joining could be realized with sheet metal thicknesses of the hydroformed part starting from 1.4 mm. In figure 5 a riveted steel sheet joint is presented on the left side and a joint made of aluminium on the right side.

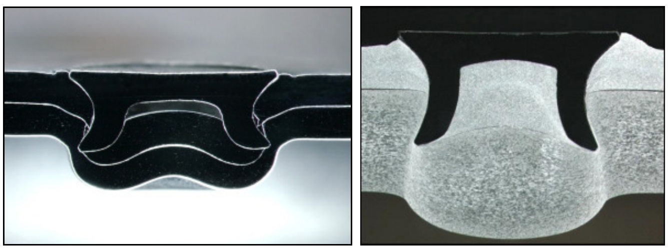

Fig. 5. Polished sections of joints created by Hydro-Self-Pierce Riveting with wobble movement, left: a joint of steel sheets (ZStE180BH 1,2 mm / ZStE260BH 1,5 mm, pressure 1800 bar), right: a joint of aluminium sheets (AlMg3 1,5 mm / Ecodal608 4,0 mm, pressure 1200 bar)

When joining with high forming velocities (impulse) a speed-dependent change of the material flow and friction conditions could be observed in the case of aluminium [4]. Although the tool speed of 10 m/s is at the lower limit range of the so called high-speed forming, very high forming velocities (up to 10^4 s^{-1}) are attainable because of the small geometrical dimensions. As a result, the deformability can be increased and thus the operational limits can be widened [5]. In order to be able to judge the strength of the manufactured joints, the hydro-joined samples were prepared and tested in the quasi-static tensile shear test. The tested material combinations showed shear tension strength for the steel joints of 4 kN and in the case of the aluminium joints of over 5 kN due to the larger sheet metal thickness. That corresponds to about 80% of the strength of conventional self-pierce rivet joints. An example of a force-trajectory curve from the quasi-static tensile shear test is represented in figure 6.

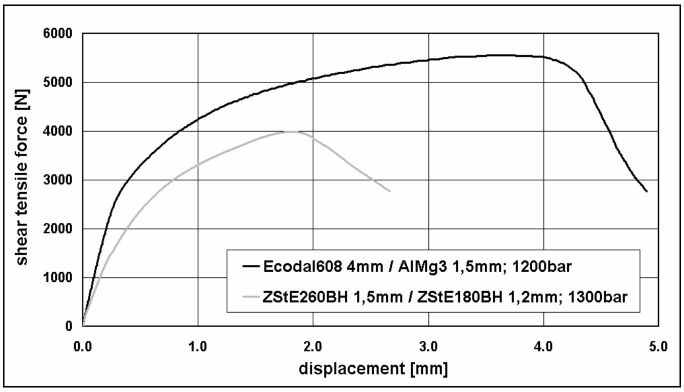

Fig. 6. Shear tensile strength of joints of aluminium and steel sheet metal (Böllhoff self-pierce rivet 35B2, hardness 330 HV10)

5.2 Hydro-Clinching

In case of **Hydro-Clinching** the size of the interlock depends on the geometrical properties of the hole chamfers in the part to be attached, on the material flow of the bulb and on the internal pressure. In the experiments the diameter of the clinching spots was varied from 17 mm to 22 mm. Exemplary the figure 7 shows the cross sections of manufactured joints, on left side for a mixed joint and on the right side for a steel joint.

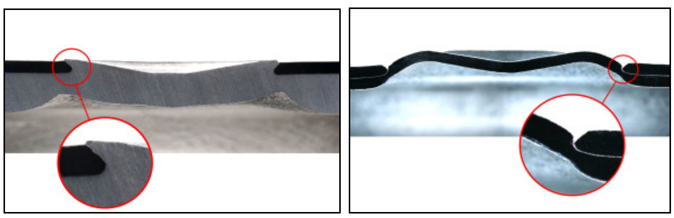

Fig. 7. Cross sections of joints created by Hydro-Clinching with active punch movement; left: DC04 1,0 mm / AlMg0,7Si 4,0 mm; point diameter 17,5 mm; pressure 1600 bar, right: ZStE180BH 1,2 mm / ZStE260BH 1,4 mm; point diameter 22,0 mm, pressure 1400 bar

In the figure at the left, depicting the mixed joint, we see that for an angle of 45° there is a clear interlock. Where as in the figure at the right, because of the small thickness of the lower steel sheet, there is only a small interlock to be seen. An additional traction results of the radial compression stresses the contact zone. Beside the material properties, the punch arrangement has also an influence on the interlocking of the sheets, whereby a slight punch feed motion (of 2 mm in the example) leads to a larger interlock. The strength of the joints was determined in the quasi-static tensile shear test. The tested steel-aluminium joints were tested for up to 8 kN. And due to the smaller sheet metal thickness, the steel joints were tested for up to 5 kN.

6 MODEL VERIFICATION AND OPTIMISATION

The experimental verification of the processing model for hydro joining takes place via comparison of measured and computed process variables and joint geometry. For example the figure 8 show how good the agreement between experiment and simulation can be. The processing models regarding plastic material behavior, friction and pressure ratios could be improved and an optimization of the geometrical formation of the joint and the processing could be made by the confrontation of the test results. Figure 8 shows cross sections of a Hydro Clinching joint with rigid punch and optimized connection with active punch movement and improved punch front angle in experiment and simulation.

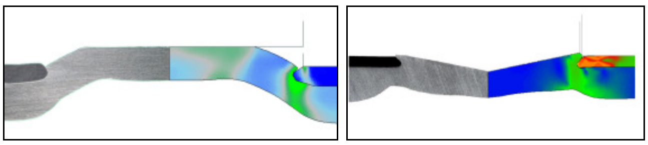

Fig. 8. Comparisons between experimental and simulated sections of hydro clinched sheets. left: joint with stationary and plane punch right: optimized joint with active punch movement and punch front angle of 160°

7 CONCLUSIONS AND OUTLOOK

In a set of joining experiments it could be proven that both procedure variants work for joining identical materials and for joining of steel and aluminium alloys. The advantages of the hydro-joining processes are in the decreasing of the number of processing steps and in new design possibilities, as joining in complex hydroformed units becomes possible also in inaccessible places. On the basis these procedures were developed special functional elements to joining during hydroforming. Figure 9 shows an example of a joint with a threaded pin.

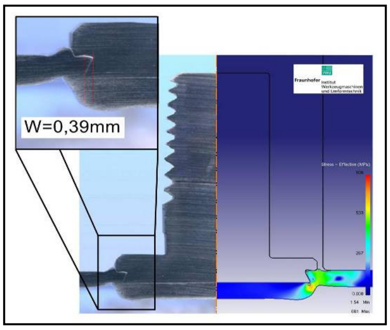

Fig. 9. Comparison between experimental and simulated section of hydro functional element (DC04, 1,5 mm)

The high accuracies of the hydroforming technology can be maintained by the cold joining technology, which represents a large advantage in relation to the welding methods used so far. The joining operation can be accomplished without extension of the process time for example during the calibration step.

ACKNOWLEDGEMENTS

The autors would like to thank the DFG “Deutsche Forschungsgemeinschaft”, Germany, for the financial support of the project as part of the research priority Program SPP 1098.

REFERENCES

1. R. Mauermann, Neuere Beiträge zum mechanischen Fügen, 6. Sächsische Fachtagung für Umformtechnik, Dresden 1999, pp. 346-359.
2. R. Frobin, Abhängigkeit des Umformvermögens vom Spannungszustand und Möglichkeit zur Umformung spröder Werkstoffe, 2. Sächsische Fachtagung Umformtechnik, Freiberg, 1995, pp. 11./1-24.
3. W. Dahl, R. Kopp, O. Pawelski, Umformtechnik, Plastomechanik und Werkstoffkunde, Springer 1993, p. 303
4. R. Neugebauer, A. Schubert, Influence of increased strain rate on flow strenth and friction during microforming, Advanced Technology of Plasticity 2002 (Proceedings of the 7th International Conference on Technology of Plasticity) Volume 2, Yokohama, Oct. 27th - Nov. 1st 2002, pp. 397-402
5. R. Neugebauer, R. Mauermann, R. Grützner, Hydrofügen - konventionelle und impulsförmige Krafteinleitung; 3. Kolloquium "Wirkmedienbasierte Fertigungstechniken zur Blechumformung" DFG-Schwerpunktprogramm SPP-1098, Stuttgart, 10. Dezember, 2003, S. 57-64