Journal of Machine Engineering, Vol. 17, No. 1, 2017

Received: *20 December 2016* / Accepted: *05 January 2017* / Published online: *13 March 2017*

tube forming, mechanical joining, upset bulging, local heating, servo press

Alexander SVIRIDOV[1*]
Philip GRÜTZNER[2]
Michael RUSCH[1]
Markus BAMBACH[1]

JOINING BY UPSET BULGING – TOOLING DESIGN AND NEW CONCEPTS FOR ONLINE PROCESS CONTROL USING SERVO PRESSES AND LOCAL HEATING

Conventional fusion-welding techniques pose limitations in modern multi-material assemblies due to the heat input. The negative influence of the heat-affected zone on the material properties must be avoided particularly in high-strength steels. During mechanical joining processes, which may also be used for joining of different materials e.g. steel and aluminium, high-performance joints can be produced without degradation of the material properties. Joining by upset bulging is an innovative joining method based on plastic buckling of tubes under axial compression. In previous investigations of joining by upset bulging the process parameters were determined and joints of tubes with sheet metal were tested under static and dynamic loads. The results of these studies have shown that the process of upset bulging has a large potential for the production of joints of tubes with sheets and plates. The present paper focuses on the tooling concepts for an efficient use of the technology and describes methods to control the forming and joining process. Two aspects are covered: (i) the application of servo-presses for joining by upset bulging and their possibilities for on-line process control, (ii) a moderate, process-integrated local heating of the forming area to avoid the formation of cracks and to further increase the strength of the joints.

1. INTRODUCTION

Continuous efforts to reduce emissions in transport and to improve resource efficiency in industrial production processes define a need for innovative lightweight designs and corresponding manufacturing processes. Precisely with regard to current multi-material designs mechanical joining processes can be used profitably, since welding processes are subject to limitations due to the high heat input in the joining zone. Particularly for high-strength materials it is very important to avoid heat input. Various mechanical joining processes like clinching or riveting are used for connecting sheet metal parts while joining by upset bulging is applied to join tubes with sheets, plates or similar parts. To create such

[1] Brandenburg University of Technology Cottbus-Senftenberg, Chair of Mechanical Design and Manufacturing, Germany
[2] HTW Berlin, University of Applied Sciences, Berlin, Germany
[*] E-mail: sviridov@b-tu.de

an assembly, a revolving flange is formed in a tube under axial load to allow the insertion of a pierced sheet metal. A second flange is formed in the same way on the opposite side of the sheet, which clamps the sheet metal part and creates a form and force fit (Fig. 1.). The main process parameter for upset bulging is the free length of the tube between the tools before the forming of a bulge („bulging length”).

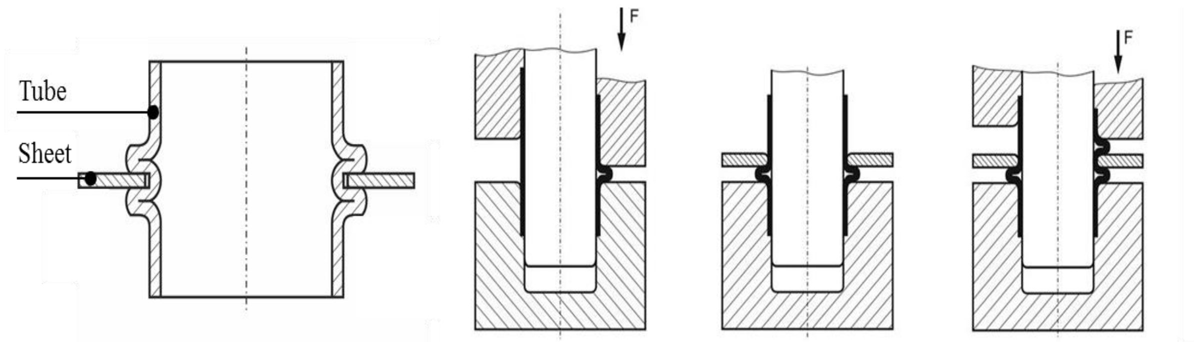


Fig. 1. Cross section of tube-sheet-joint and standard upset bulging process (schematic)

Joining by upset bulging has advantages over welding concerning cycle times, possibilities for process automation and the use of different types of material. The mechanical properties of the materials are retained because the microstructure is not negatively influenced by heat input.

A basic description of joining by upset bulging is given by Lange [1] and Spur et al. [2] and further studies on joining a tube with a sheet metal were carried out by Alves et al., Viehweger et al. [3] and Grützner [4]. Alves et al. examined the joining of a sheet metal part to the end of a tube with a two stage process [5]. Later the authors introduced a single-stroke process [6]. The process parameters and their influences were identified by experimental and numerical means. They also investigated the joining of tubular parts to each other in an axial end-to-end orientation and other (asymmetric) arrangements with the feasibility for multi-material-joints [7],[8]. All of these studies were performed at room temperature. Although they show the great potential of joining by upset bulging. Viehweger et al. [9] investigated the joining by upset bulging at room temperature in detail with regard to the formation of cracks and damage in the buckling zone. It was found that the risk for damage and cracks increases with greater bulging lengths. A working range for the steel E235+N and several tube dimensions was identified by experimental und numerical process analysis. Static and dynamic testing of the joints was performed with lower bulging lengths reaching higher loads in tensile testing and bending. A fatigue curve was determined for an exemplified tube-sheet-joint.

In this paper, a method to perform joining by upset bulging with servo presses is described. This procedure incorporates reliable on-line process control and is suitable for series production. Secondly a local heating (up to 700 °C) of the forming area is introduced to further improve the quality of the joints and to increase the strength of the bulges when applying static and dynamic loads.

2. JOINING BY UPSET BULGING WITH SERVO PRESSES

The industrial implementation of joining technologies demands an extensive knowledge about machines, tools and process control. Additionally there are strong interactions and subjections between these fields.

As shown in Fig. 2 electromechanical spindle presses, also known as servo presses, are characterized by a simple structure and advanced opportunities in the field of process control. Based on the mechanical setup, the force is available in every position between upper and lower position. Basically, the technology includes all benefits of conventional hydraulic and mechanical presses. In most cases the motor is connected directly with a ball- or roller gear drive as shown in the picture. Positioning accuracy up to ±1 μm can be reached with this technology.

In the current investigations a 300 kN press by Promess Gesellschaft für Montage- und Prüfsysteme mbH with an internal measuring-system and an additional external system with displacement transducer by Heidenhain was used. For the force measurement internal and external sensors were integrated, so that very precise measurements were possible. The data-recording and processing was done by the special machine software PROMESS V5, which is usable for all industrial joining processes.

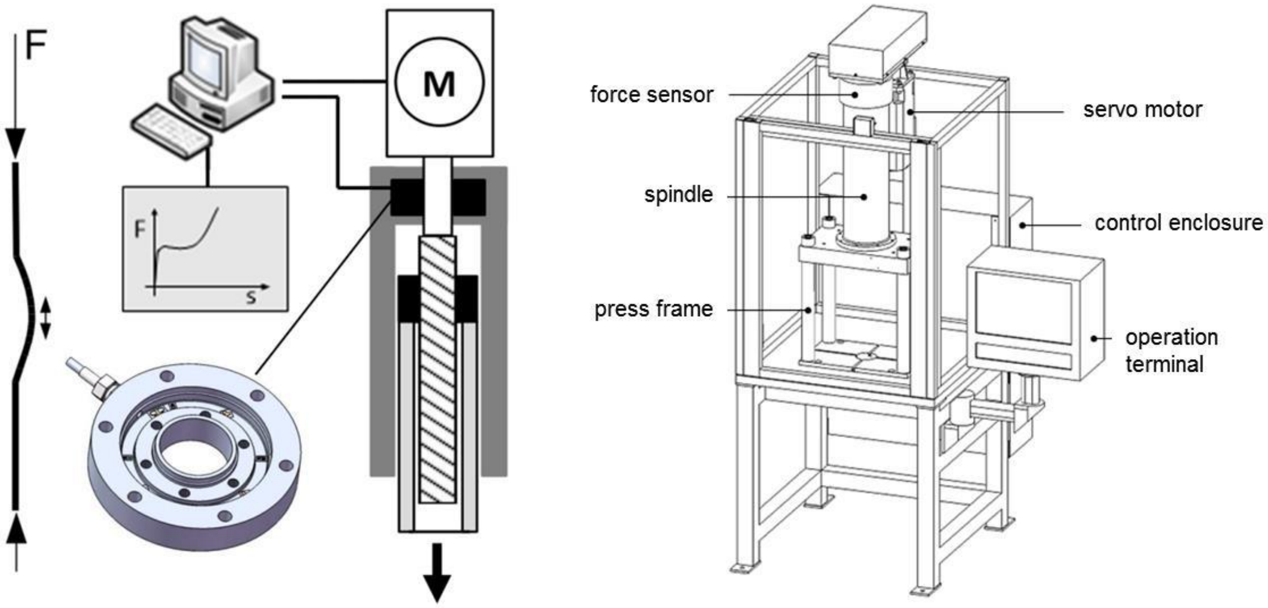


Fig. 2. Structure of a servo spindle press

One of the most challenging jobs is the implementation of a suitable tool-method, especially in the field of joining by forming. Fig. 3 shows a prototyping tool, which was created for the testing of industrial use. It consists of an upper die with a spring-loaded inner die and a bottom die. And in contrast to the simple process shown in Fig. 1, there is an additional spindle-drive in the bottom die, which is needed for the removing of the parts after the forming process. There are also clamping claws for fixing and an easier deforming of the tube ends. Additionally two strippers are integrated, which can be moved in the radial direction.

Position 1 and 2 represents the forming of the 1st bulge. The 3rd picture shows a synchronized motion step of the upper die and the spindle drive. This step is necessary for removing the tube and providing the material for the 2nd bulge. Position 4 is the 2nd forming-process. Then in the 5th picture the inner die is being removed from the tube. This is done by the stripper. And in the last step, the stripper is being removed and the part is being ejected with the spindle drive in the bottom die. Altogether there are many detailed problems, which have to be solved in an industrial manufacturing process. The most used control strategies in the field of forming and joining technology are force and distance control. On the one hand, force control can balance manufacturing tolerances, but on the other hand, precise positioning is not possible. Additionally the machine has to be adjusted to the worst case force. In contrast, position control in combination with large tolerances leads to a wide range of process forces, which is also not useful in most cases.

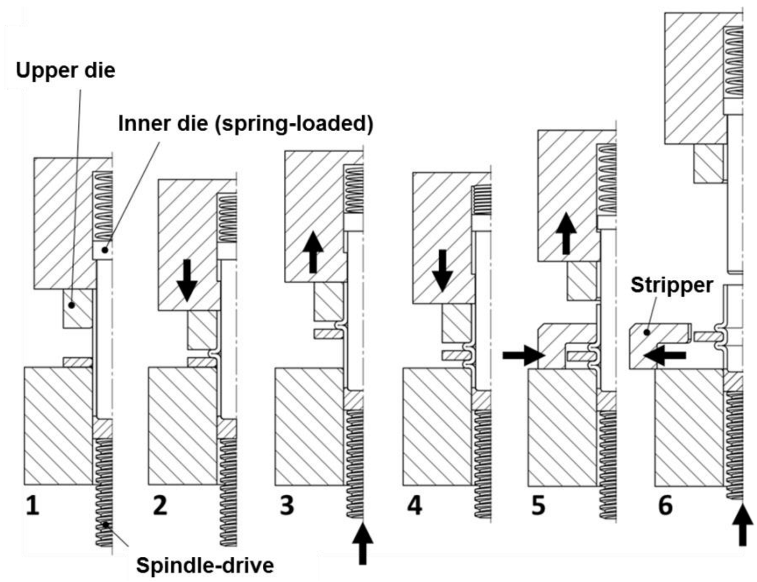


Fig. 3. Upset bulging prototyping tool for manufacturing tests

In the course of the investigations a suitable combination of force- and position control for the upset bulging process was developed. As shown in Fig. 4, the final position is detected by a gradient-change in the force-displacement curve. This can be very useful, especially for a wide range of process parameters, because the load affecting the machine and the tools can be reduced significantly.

Another benefit is, that the upper and the lower control curves can be fixed subjected to the bulging point, also detected by a gradient-change. This leads to higher control-quality. The upset bulging process is characterized by wide tolerance ranges. The critical load and the process force depend on the cross-area-section of the tube and are additionally influenced by wall-thickness- and yield strength-tolerances.

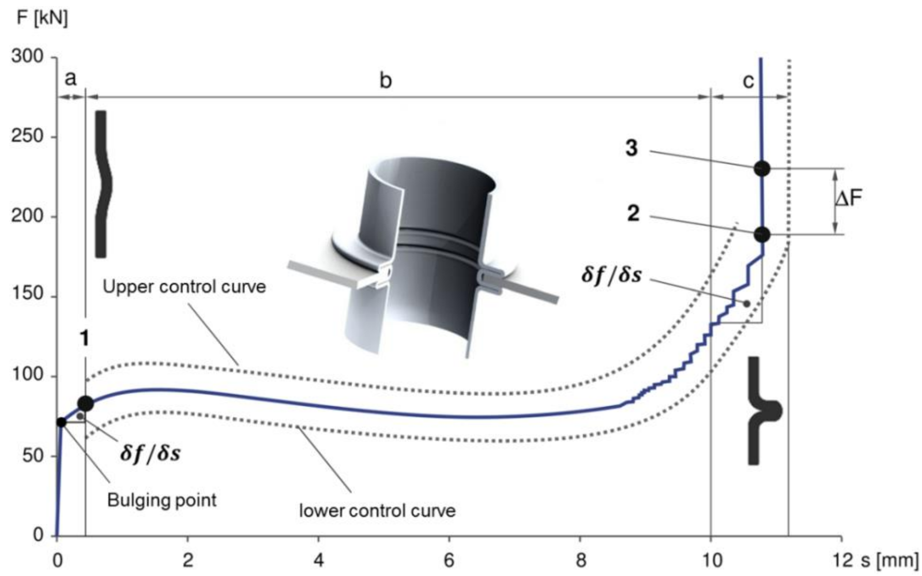


Fig. 4. Force-displacement curve and upset bulging process control strategy

Another benefit is, that the upper and the lower control curves can be fixed subjected to the bulging point, also detected by a gradient-change. This leads to higher control-quality. The upset bulging process is characterized by wide tolerance ranges. The critical load and the process force depend on the cross-area-section of the tube and are additionally influenced by wall-thickness- and yield strength-tolerances.

3. UPSET BULGING WITH LOCAL HEATING OF THE FORMING AREA

Forming at room temperature could be limited due to very high forces needed to plastically deform a workpiece. Additionally high strains and stresses may occur in the forming area. This could lead to the formation of cracks and failure of the workpiece (Fig. 5). Warm forming leads to reduced yield stresses and better deformability of several materials (e.g. steel).

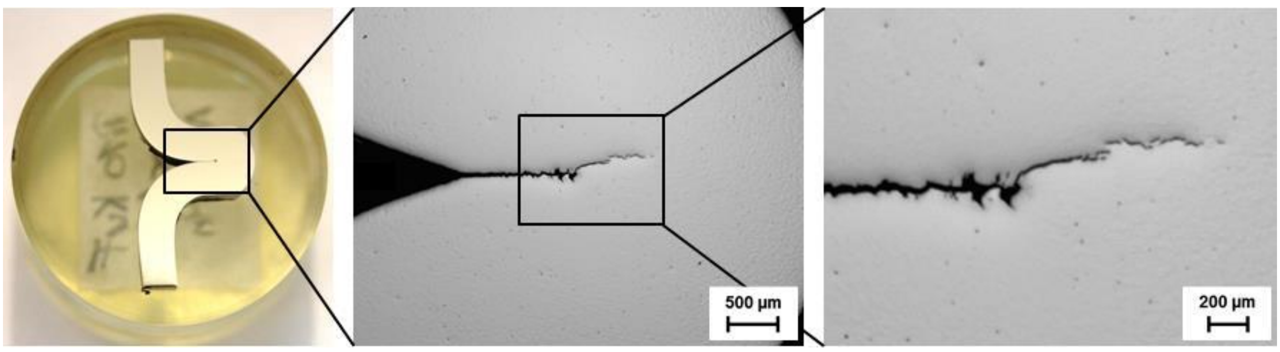


Fig. 5. Crack in the inner radius of a bulge formed at room temperature

Since the microstructure and the mechanical properties of the material should not be influenced by the temperature, it is necessary to limit the heating process that no phase transformation takes place. For economic reasons the heat-affected zone should be as small as possible. In ferritic steel, the transformation of α-ferrite to γ-austenite starts at a temperature of at least 723°C so the maximum temperature for the examinations in this paper was 700°C to avoid phase transformation.

3.1. EXPERIMENTAL SETUP FOR INDUCTIVE HEATING

To achieve a fast and efficient heating of the tubes, an inductive heating unit was used. Inductive heating allows a contactless heating of conductive materials. The temperature is controlled by a pyrometer and a control unit in the induction generator. The generator offers a maximum power output of 15 kW in a medium frequency range (10 – 25 kHz). The supporting unit, which was developed in house, offers electrically driven adjustable axes to orientate the induction coil towards the tube. After heating, the coil could be removed in the same way. Two different induction coils were compared. Firstly a standard rigid ring inductor (height: 41 mm) was used for basic heating experiments. Secondly a special split inductor was employed (height: 5 mm). Tubes made of the steel E235+N with the dimensions Ø 40 mm and wall thickness of 2 mm were used.

The split inductor has shown several advantages over the rigid ring inductor. Since the ring inductor cannot be opened, an additional infeed in the axial direction of the tube is needed to remove it from the operating area of the press. After that the tool can be closed to start the forming process. However the split inductor can be opened after heating and the forming process can start immediately (Fig. 6). At the same time the inductor can be moved out of the operating area of the press. The process time is significantly reduced.

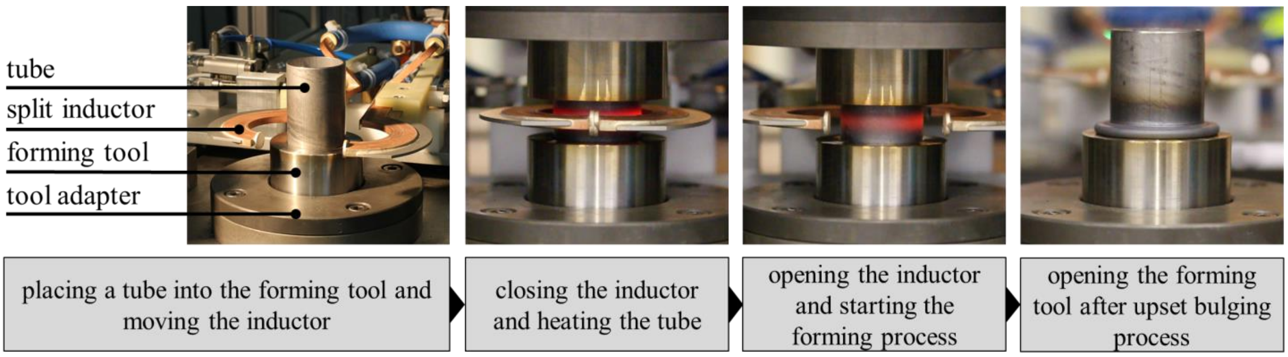


Fig. 6. Steps of the upset bulging process with local heating by split inductor

The narrow height of the split inductor also creates a smaller heat-affected zone on the workpiece (Fig.). The tube area out of the heating zone is only slightly heated by thermal conduction with no impact on the process or workpiece. To create a tube-to-sheet-joint, two forming steps are needed (Fig.1).

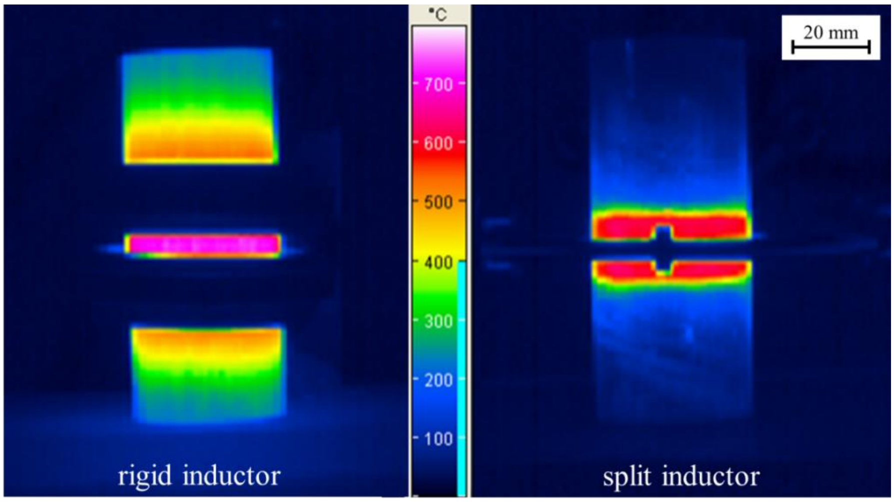


Fig. 7. Thermal images of the induction coils

The inductive heating process adds an additional step before each forming step. First the induction coil is placed in the particular (upper) forming area. After the heating and opening of the induction coil the forming process starts (Fig. 8, step 1). In step 2 the first bulge is finished and the tools open slightly to remove the split spacer ring and unblock the lower forming area. The inductor is positioned accordingly. After another local heating process, the second bulge forming begins in step 3. Step 4 marks the end of the process with a completed tube-to-sheet-joint. The same heating strategy can be used in the forming process, which was illustrated in Fig. 3. The heating process can be integrated in the steps 1 and 3.

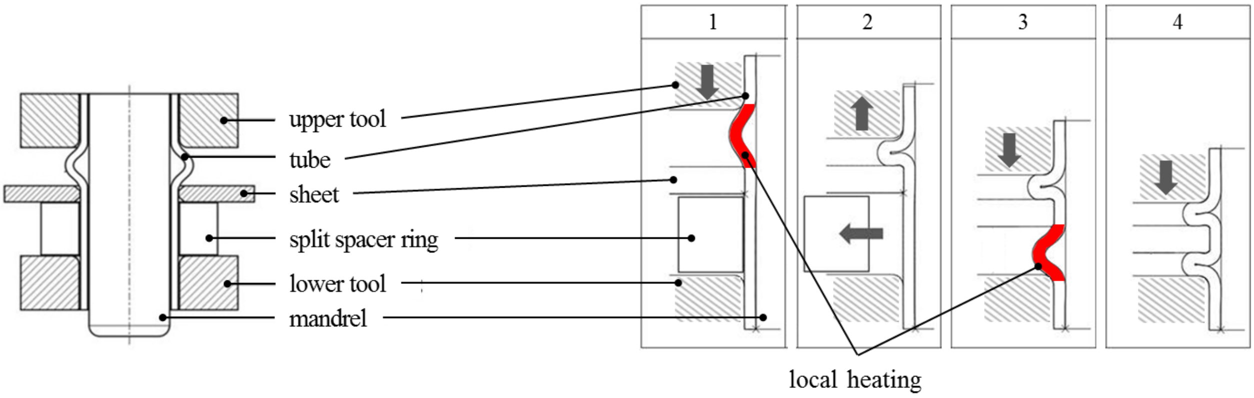


Fig. 8. Joining by upset bulging process aligned to local heating

With the above described procedure it was possible to create tube-to-sheet-joints as shown in Fig. 9. The dark areas next to the bulges represent the relatively small heat-affected zone while the rest of the tube was surrounded by the forming tools which dissipated the heat from the tube.

Fig. 9. Tube-to-sheet-joint – tube Ø40x2 mm – sheet 5 mm

3.2. METALLOGRAPHIC INVESTIGATIONS OF THE WARM FORMING AREA

Bulges formed at room temperature are subject to the formation of cracks due to high strains and stresses during the forming process. The probability for this type of damage increases with a greater bulging length. To form a crack-free bulge, inductive heating of the forming area was used. After forming small sections from the bulges were cut out and prepared for the metallographic inspection with a light-optical microscope. Bulges formed at 500°C with a bulging length of 15 mm showed little cracks left in the inner buckling zone. At lower temperatures the material is stiffer so that the crack formation is even more likely. At 600°C and 700°C no cracks could be identified in the metallographic cross sections. Also with increased bulging length of 20 mm it was possible to form a crack-free bulge (Fig. 10).

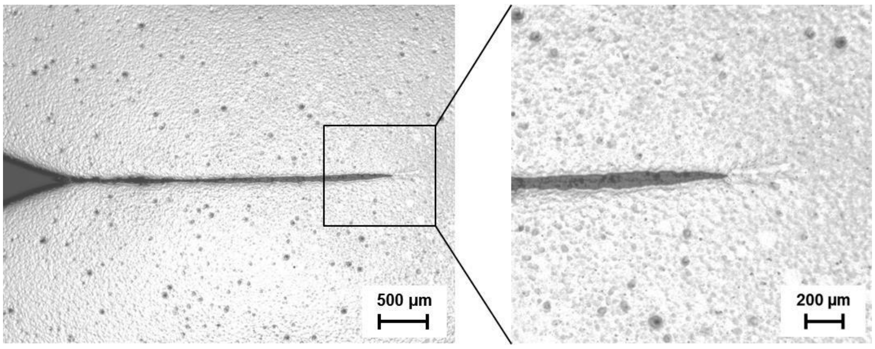


Fig. 10. Crack-free bulge formed at 700 °C

3.3. DYNAMIC TESTING OF THE BULGES

The bulges formed with local heating (700°C) were compared to bulges formed at room temperature under dynamic loads. For dynamic tensile testing a servo hydraulic testing machine (Instron I8801) was used. The samples were equipped with steel plates, which were welded at both ends of the tube and two M12 screws to fit into the machines mount. The dynamic load was applied according to a sinusoidal function with a frequency of 20 Hz, a maximum load of 20 kN, a lowest load of 2 kN and an average load of 11 kN. Fig. 11 shows a 0.5 second section of the function.

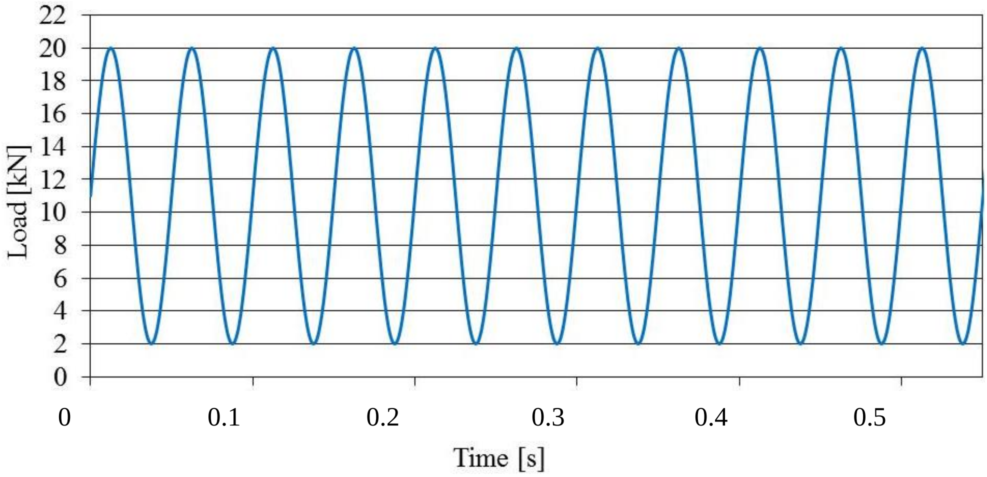
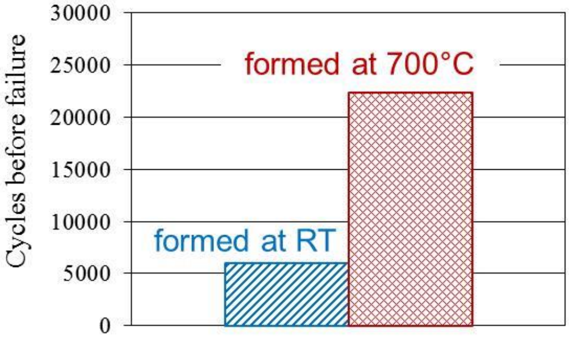


Fig. 11. Sinusoidal function of force during dynamic testing

The fatigue behaviour for room temperature and heated samples was significantly different. While room temperature samples reached an average of 6046 cycles before failure, heated samples reached an average of 22321 cycles. For both types of samples the same tube material (Ø40x2 mm, E235+N) was used. The tubes were formed with a bulging length of 15 mm.

Failure occurred in the middle of the bulge for both types of samples. The much earlier failure of the room temperature samples originates from the pre-testing cracks in the bulging area, while the heated samples were crack-free. Because of the notch effect of the small radius in the inner buckling area, the formation of cracks and the following failure was also initiated in the middle of the bulge for the heated samples. Fig. 12 shows the diagram of cycles before failure and a sample at the end of testing.



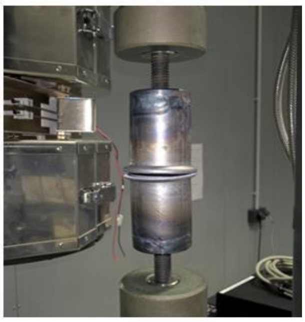


Fig. 12. Left: Cycles before failure for dynamic testing, Right: Sample at the end of testing

4. CONCLUSION

Joining of tubes with sheet metals by upset bulging is described in this paper. The mechanical joining process is suitable for numerous applications for example multi-material designs when other joining techniques (e.g. welding) suffer from limitations. An efficient and well controllable way of series production is possible by using servo presses due to advanced means of process monitoring and control. A combined method for process control with force and position observance during the forming process was developed. This guarantees a high quality of parts and reduces loads on the machine and tools. A prototype scale tool concept was introduced providing multiple spindles for forming and ejection of the parts. The parts quality is also influenced by the processing technology. Bulges formed at room temperature from the construction steel E235+N show occasional damage (cracks) in the bulge area due to high stresses and strains during forming. A way to avoid the formation of cracks is a local inductive heating process before forming a bulge. A heating unit was developed using a special split inductor to attain efficient process integration. Metallographic investigations confirmed a crack-free bulging at 700°C for E235+N tubes. Dynamic testing was carried out where the heated samples outperformed samples formed at room temperature. Further research in the field of joining by upset bulging may concern the joining of different materials and the application of alternative arrangements of parts (e.g. tube-tube-joints) with adapted geometry of bulges.

ACKNOWLEDGMENTS

The projects "Joining by upset bulging" (Ref.-No. AiF 17312BG) and "Process optimization of joining by upset bulging using local warm forming" (Ref.-No. AiF 17639BG) were financed and supervised by the European Research Association for Sheet Metal Working (EFB). In the scope of the programme to promote Industrial Collective Research they were funded by the German Federation of Industrial Research Associations (AiF) with means of the Federal Ministry of Economic Affairs and Energy (BMWi) on the basis of a decision by the German Bundestag.

REFERENCES

[1] LANGE K., 1993, *Umformtechnik Handbuch für Industrie und Wissenschaft Band 4: Sonderverfahren, Prozeßsimulation, Werkzeugtechnik, Produktion*, Springer-Verlag, Berlin Heidelberg.

[2] SPUR G., STÖFERLE TH., 1986, *Handbuch der Fertigungstechnik Band 5 Fügen Handhaben Montieren*, Carl Hanser Verlag, München Wien.

[3] VIEHWEGER B., SVIRIDOV A., GRÜTZNER P., BEHRENS B.A., BOUGUECHA A., ALMOHALLAMI A., 2015, *Ermittlung von Verfahrensgrenzen für das Fügen durch Knickbauchen anhand des Werkstoffes E235+N*, Materialwissenschaft und Werkstofftechnik, 46/8, 804-812.

[4] GRÜTZNER P., 2014, *Prozessentwicklung für das Fügen durch Knickbauchen*, Dissertation, BTU Cottbus-Senftenberg.

[5] ALVES L.M., DIAS E.J., MARTINS P.A.F., 2011, *Joining sheet panels to thin-walled tubular profiles by tube end forming*, Journal of Cleaner Production, 19, 712-719.

[6] ALVES L.M., MARTINS P.A.F., 2013, *Single-stroke mechanical joining of sheet panels to tubular profiles*, Journal of Manufacturing Processes, 15, 151-157.

[7] ALVES L.M., SILVA C.M.A., MARTINS P.A.F., 2014, *End-to-end joining of tubes by plastic instability*, Journal of Materials Processing Technology, 214, 1954-1961.

[8] ALVES L.M., MARTINS P.A.F., 2012, *Tube branching by asymmetric compression beading*, Journal of Materials Processing Technology, 212, 1200-1208.

[9] VIEHWEGER B., SVIRIDOV A., GRÜTZNER P., BEHRENS B.-A., KAMMLER M., ALMOHALLAMI A., 2014, *Fügen durch Knickbauchen*, EFB-Forschungsbericht 395, Europäische Forschungsgesellschaft für Blechverarbeitung e.V., Hannover.