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ORIGINAL ARTICLE

Manufacturing of resistant joints by rolling for light tubular structures

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Abstract The idea of joining by rolling emerged as an alternative to existing joining and assembling methods for lightweight frame structures, offering flexibility in manufacturing, low costs and simplicity in handling. The present paper deals with research work on joining of nodes in tubular aluminium structures by external rolling accompanied by applying glue. Special attention was paid to the node resistance and material behaviour when rolling by means of a one-roller burnisher and a multi-roller burnishing head.

Keywords Joining by forming · Rolling · Aluminium tubes · Bonding

1 Introduction

Contemporary manufacturing, working, and end user's requirements demand low-cost and reliable lightweight frame structures in combination with flexible manufacturing. These requirements can be met by applying flexible methods of joining tubes by rolling as an alternative to conventional technologies. Joining of mechanical parts is one of the most important technologies in the manufacturing chain. It influences the assembly/disassembly processes and highly influences an economical, efficient, flexible and competitive design of all mechanical structures.

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Joining of tubes represents an important issue in engineering, and especially in hydraulics and frame constructions. In the case of lightweight constructions, the weight and resistance factors play a substantial role. In recent years, the industry has focused on lightweight constructions and the use of aluminium tubes presents a promising solution for resistant and cheap tubular structures. Critical engineering aspects of tubular structures can be found in nodes where two or more tubes have to be joined together (Fig. 1). Classical methods comprise many joining solutions and technologies. Joining methods may be classified into several groups and their division is in accordance with DIN 8593. Many of them, such as screwing and welding, belong to conventional methods and are successfully used up to now. Plastic deformation-based technologies [13] seem to be the most promising ones as to easy-to-use techniques, compared with other techniques and methods.

As joining of tubes constitutes an important aspect of assembly processes the progress in technology constantly reveals new procedures and techniques. In recent years, interesting experiments have started as to research potentials for joining tubes by plastic deformation methods. Main technologies offered to the designers which can be used for joining by plastic deformation (Fig. 2) are: electromagnetic forming, hydroforming and mechanical forming.

Interference-fits produced by the technologies mentioned above depend on the dominating strains in elastic, elastic-plastic and full-plastic interference-fits [5]. A joint can be produced by compressing a tube on another joint partner or by expanding a tube in a joint partner. The force which determines the forming of the tube, leads to an elastic-plastic deformation of the tube and an ideally elastic deformation of the other joint partner. After this, a corresponding elastic recovery of both joint partners occurs.

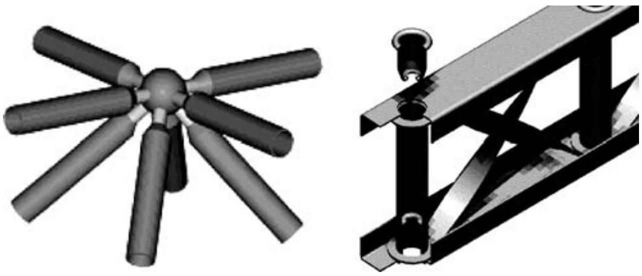


Fig. 1 Nodes of tubular frame structures (*Sunlite Australia*)

If a full relaxation of the joint partner is prevented by the tube, a permanent pressure in the radial direction is established. This pressure is a balanced condition of the joint partners stress relief, on the one hand, and the resulting reinduced stress in the tube, on the other hand. The strength of interference fits strongly depends on the area of the contact zone, the friction coefficient, and the remaining interference stress within the contact zone [11].

Electromagnetic forming (EMF) is a high speed forming process using a pulsed magnetic field to form metals with high electrical conductivity such as aluminium. The energy density of a pulsed magnetic field is used for the contactless forming of a workpiece. Joining is the most common industrial application of the EMF-process. Due to the contact-free forming process the joining of coated fuel pipes is a feasible application. Furthermore, joining of composite materials as well as structural components is of

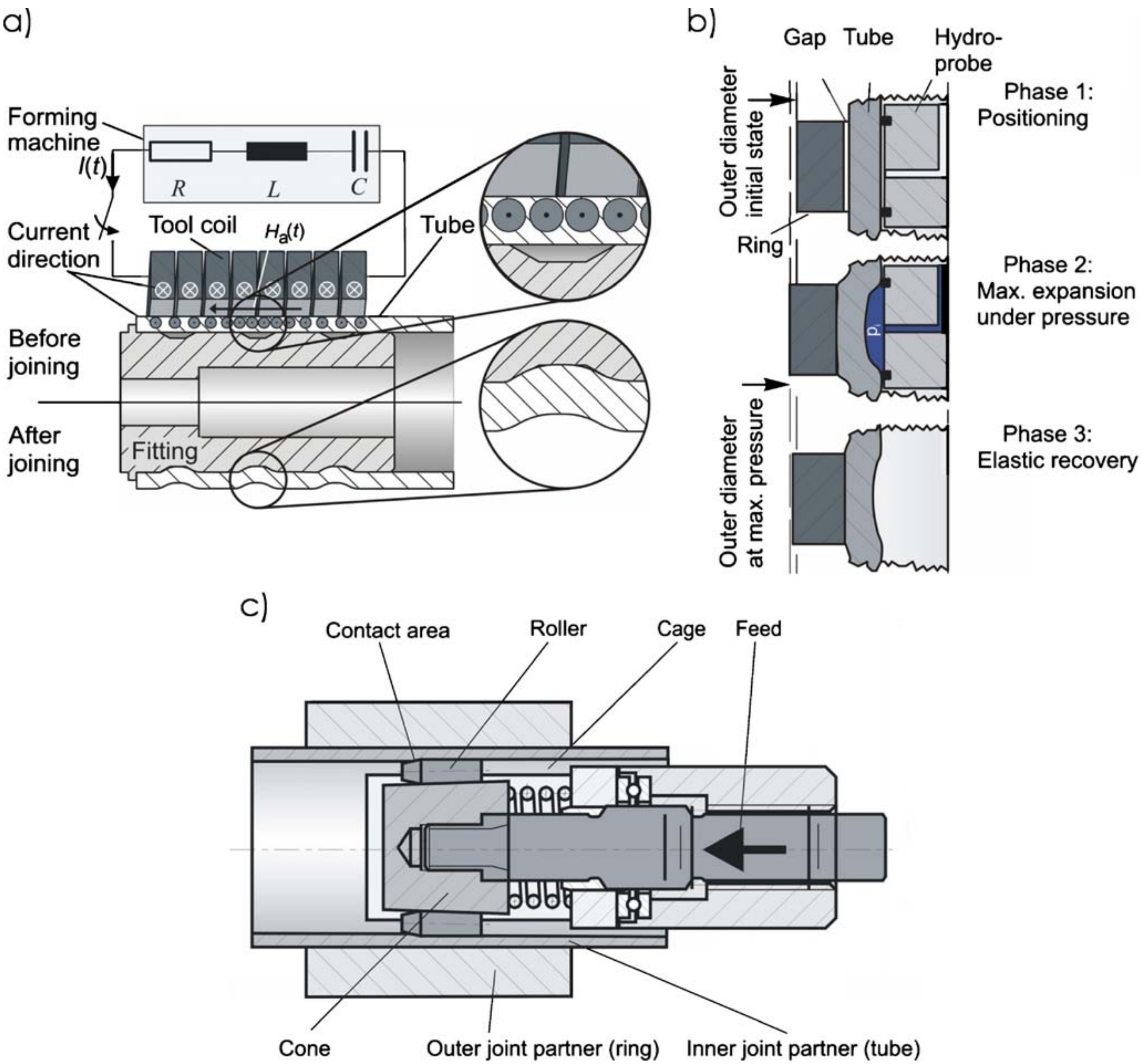


Fig. 2 Joining by forming: **a**) electomagnetic forming, **b**) hydroforming, **c**) mechanical forming (rolling example)

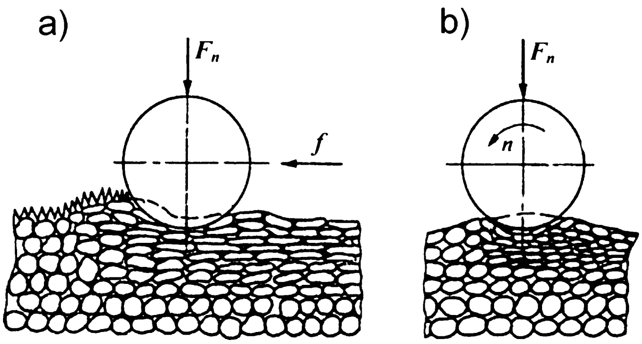


Fig. 3 Scheme of plastic deformations in the surface layer of ball-rolled shaft: **a**) longitudinal section, **b**) cross-section

increasing interest. Fig. 2a displays the principle of the EMF-joining process. Especially for structural components made of aluminium alloys (with good electrical conductivity) the EMF-process is suitable and of increasing interest [2, 11].

Assuming a good process design, the quality of these joints can satisfy the criteria of strength or impermeability even for the aerospace or automotive industry. New developments in the field of tool coil design allow forming and joining of non-cylindrical profiles as well as completely closed frame structures.

Examples of numerous investigations, including experiments and mathematical approaches, can be given among others research work at the University of Dortmund, Ford Research Laboratory in Deaborn and the National University of Seoul. Research work at Ford [7] and in Seoul [14] concentrated on the influence of working parameters and grooving of the joint interface on the axial/torque strength of tubular joints. At the same time the joining process and design of cylindrical tubular joints made of aluminium were investigated in Dortmund [1, 3] and recently the research has been spread into other aspects of electromagnetic joining by forming. All mentioned research were carried out for joining of sleeves (rings) on the mandrel by electromagnetic compression.

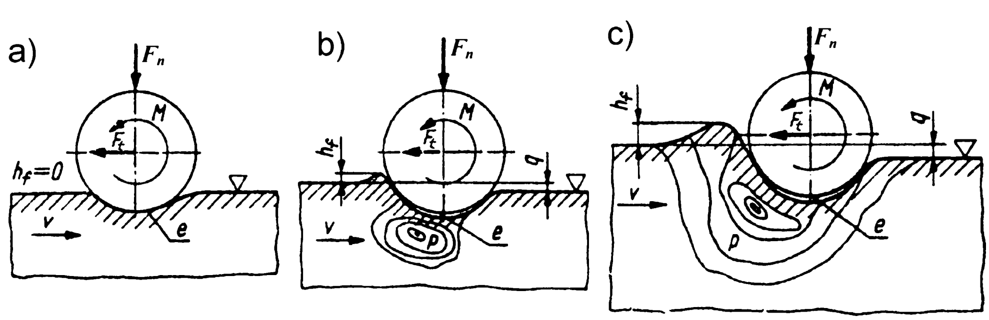
In the 1980s joining by hydro-forming was introduced in the manufacturing of heat exchangers for nuclear power plants. New developments in the field of powertrain components introduced this joining process in the automotive industry [8]. Exemplary applications are, e.g. the manufacture of camshafts, intermediate shafts, and countershafts as well as the joining of cylinder liners [17]. In case of hydroforming the pressure acts locally underneath a certain joining area instead of pressurising a complete semi-finished part, used in conventional hydro forming processes of tubes and sheet metal (Fig. 2b). The joining area is pressurised by a special joining tool, introducing it as hydro-insert. The hydro-insert is introduced into the tube, then the working medium is set under pressure after filling the gap, limited by sealings between the insert and the inner surface of the tube.

Over the last years hydroforming of joints has been subjected to extensive research work focussing on hydro-expansion/hydrobulging processes [4]. Representative centres which deal with the hydobulging issue are: University of Magdeburg, University of Dortmund, University of Clausthal. Special attention should be paid to research results obtained in Magdeburg [6] regarding joining by hydrobulging of steel joint partners. Research work at University of Dortmund by the Institute of Forming Technology and Lightweight Construction concerns joining of aluminium tubular elements by use of hydro-inserts on a special stand [11]. Extensive theoretical analysis of the phenomena appearing in the material of steel joint partners when joining has been presented by Garzke [8] and verified by experimental torsion tests.

Mechanical forming is represented by: crimping, forging, pressing and rolling. In connection with the present paper the production of joints by rolling is the most interesting important technique. Producing tubular joints is based on joining by rolling which was primarily used for joining tubes in the boiler and apparatus engineering. Water and steam tubes are joined, e.g. to the bottom of heat exchangers, e.g. for the use in power plants. Furthermore, a recent example is the manufacturing of assembled camshafts and gear shafts; this method has been successfully carried out with demonstrators for the automotive industry [12].

The process of rolling by joining can be based on the principle of roller burnishing [15]. The burnishing technology principle is based on applying a force to a roll or rollers which roll on the workpiece´s surface. Joining by rolling is done by special rolling tools using oversize levels much

Fig. 4 Simplified models of the rolling burnishing: **a**) elastic, **b**) elastic-plastic, **c**) plastic; *e*-elastic zone, *p*-plastic zone, h_f-height of the material wave



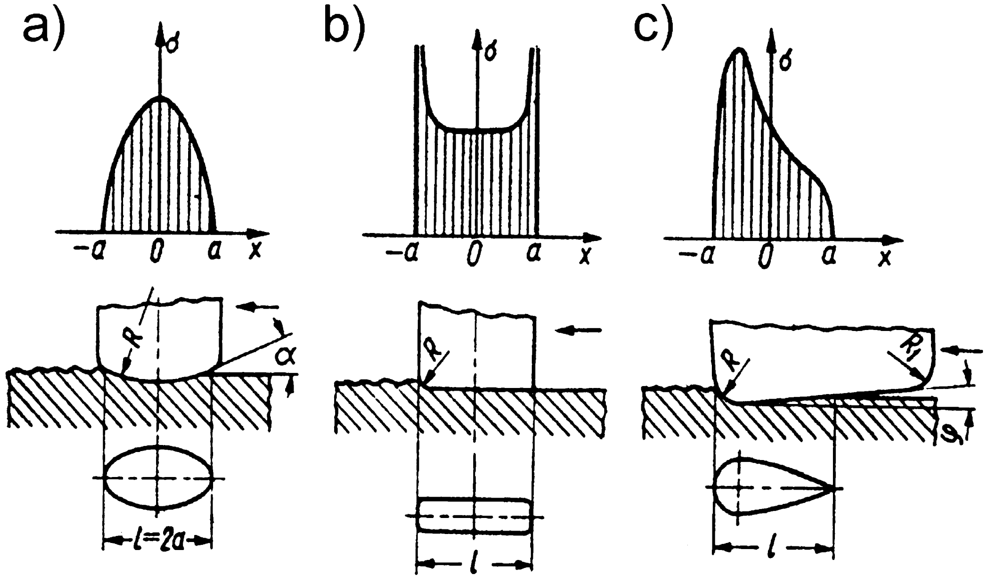


Fig. 5 Scheme of the shape of the contact zone and corresponding surface pressures for different shapes of the rolling disk: **a**) elliptical print, **b**) rectangular print, **c**) drop print

higher than those used for burnishing finishing operations. Figure 2c presents an example of joining by internal rolling. Cylindrical rolls are driven by a conical mandrel and are positioned by a cage. By an infeed of the conical mandrel the rolls are moved in the radial direction towards the tube. If the rolls produce a pressure on the tube beyond the yield stress of the material, a plastic deformation of the inner joint partner along with the elastic recovery of the outer joint partner leads to an interference fit between them [5, 10].

Contemporary research work on joining processes by mechanically induced deformations mainly focus on tubular joints made by rolling where the burnishing tool is expanding the inner tube towards the outer joint member. Consequently, the resulting deformations and stresses produce the permanent interference fit. The mentioned work was performed at the University of Dortmund in a theoretical and laboratory range [9, 12] and for industrial application on steel camshafts [10]. Further investigations were carried out by the authors for aluminium joint partners [19]. An overview of known literature and reports indicates the production of tubular joints by external rolling has not been analysed yet. Therefore, based on the former experiences and test results a corresponding research programme was performed [16]. The aim of the present paper is to present the results of this research project on joining of aluminium tubes by external rolling using burnishing tools.

2 Background and principles of joining by rolling

The burnishing technology principle is based on the application of a pressing force to a very stiff burnishing element which rolls on the workpiece and induces plastic deformations into its surface layer along with a reduction of the grain sizes and orientation of the material structure (Fig. 3) [15]. As a result, strain hardening appears in the working zone as a consequence of permanent plastic deformation. Additionally, the burnishing operation results in elastic deformations, elastic-plastic and plastic deformations. Physical models which are used in the burnishing process analysis simplify real phenomena of the burnishing process.

The rolling burnishing may be considered as rolling of a stiff cylinder on the deformable surface with presence of friction. At a certain level of force F_n, as a result of a high level of deformation, material pile-up in the form of a wave can be observed in front of the tool, which resists the rolling movement of the tool (disk, roller, or ball).

In the first stage of the deformation process, elastic deformation can be observed (Fig. 4a). In the next stage, the elastic limit of the material is exceeded and under the

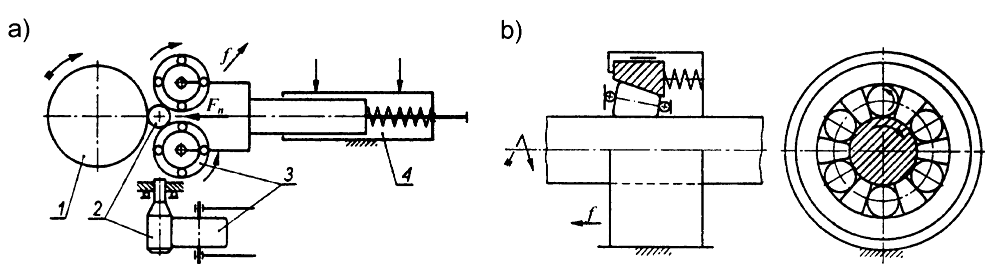


Fig. 6 Scheme of tools and devices used for burnishing of external cylindrical surfaces: **a**) spring pressure flexible one-roller tool: 1-workpiece, 2-roller, 3-supporting roller bearings, 4-square grip tool; **b**) flexible pressure multi-roller head

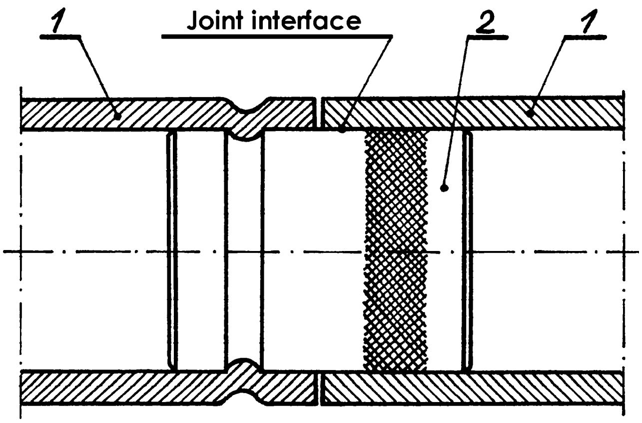


Fig. 7 Tubular joint by use of joining element: 1-tube, 2-smooth, grooved, or patterned insert

contact surface a plasticised zone is produced (Fig. 4b). When continuing to increase the pressing force, the plastic zone, which is surrounded by an elastic zone, becomes larger (Fig. 4c). The elastic zone begins to disappear and the plastic zone becomes deeper. This is the reason for the material pile-up in the form of a wave in front of the rolling tool.

The workpiece material resists the rolling action of the tool due to the deformation work. In the case of the developed deformation process, up to the plastic flow state the reaction depends on the shape of the tool-workpiece contact zone (Fig. 5) and the value of the plastifying stress. In the contact zone there are also the slip areas [18]. Surface pressure, although difficult to measure, presents the most important complex engineering indicator for rolling. As to obtain the flowing state of the material in the tool-workpiece zone, the surface pressure should exceed the value of the plastifying stress of the workpiece material.

The plastic deformation while rolling may occur in different areas

- only in the roughness zone (finishing burnishing),
- in the workpiece surface layer (strain hardening burnishing),
- deep penetrating (form rolling).

The first case of rolling is applied instead of grinding, superfinish, honing and polishing. The surface finish obtained is $R_a \geq 0{,}08$ μm. In the second case, the strain hardening and the rise in hardness up to 40% is obtained (for constructional carbon steels). The burnishing tools provide the possibility of obtaining the 6th to 7th accuracy class and can be used on typical production machine tools. In many practical cases, the burnishing operation can replace toughening and even surface hardening. In the third case, rolling can be applied for embossing of threads, toothings, grooves, and for fixing or joining by cramping the pipe joints (e.g. pipes in heat exchangers).

For the rolling process different tools and different kinds of applying pressure to the workpiece are used. It can be a flexible pressure or, more rarely used, a fix pressure. It can be imposed mechanically by use of springs or by pneumatic or hydraulic systems. An example of tools and devices used for burnishing of external cylindrical surfaces is shown in Fig. 6 [15].

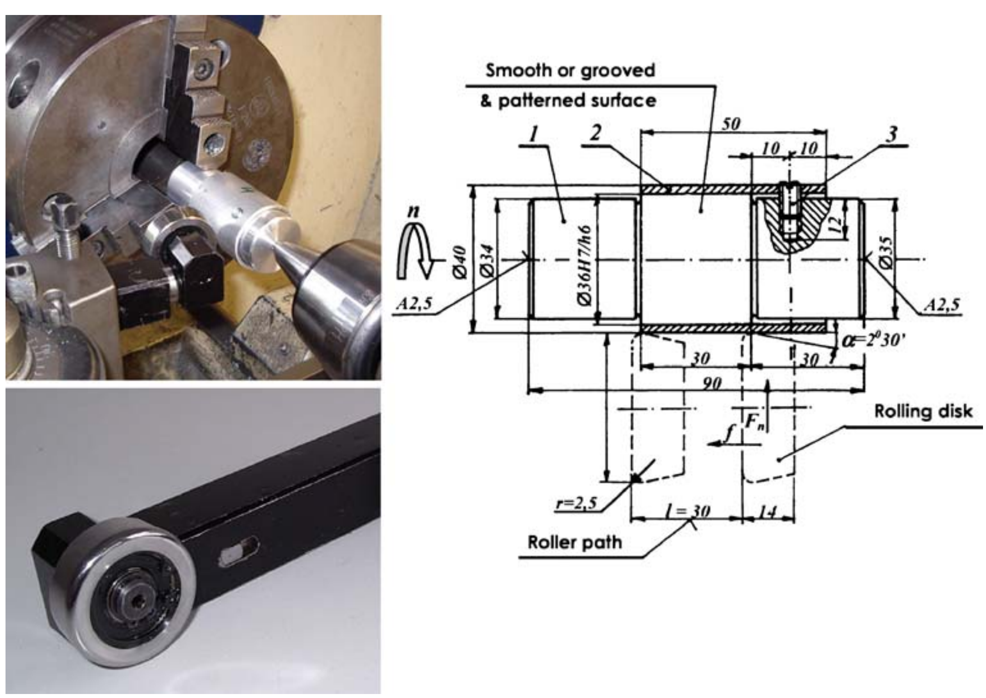


Fig. 8 Test specimen and one-roller burnisher in its working position on a lathe: 1–insert, 2–tube, 3–two stop-screws, *f*–rolling feed, F_n–rolling force

3 Target setting

As a continuation of research performed on joining by internal rolling of tubular aluminium joints [19], the basic interest of the authors in the present research work was focused on joining by external rolling of light aluminium tubes by use of insert elements (Fig. 7) as to obtain resistant joints in light tubular structures [16].

The study issue concerned researching the influence of surface formation of the joining insert element and of rolling process parameters on the joint resistance in tubular light structures produced by external rolling. Tests determined the influence of the following factors on the strength of the joint (disconnecting force when pressing the insert out of the joint):

– shape of the insert contact surface (grooving and knurling),
– the rolling parameters (rolling oversize, rolling force, and feed),
– type of tool (one-roller burnisher and multi-roller burnishing head),
– supportive applying glue onto the joint interface before rolling operation.

Test monitoring and registration were focused on:

– change of the tube specimen diameter (measured),
– elongation process of the tube specimen (measured).

Final verification of the joint quality was performed by testing the strength of the joint on a tensile testing machine.

4 Scope and execution of experiments

The tests were performed on a set of specimens which represented the shape of a real joint. The specimen consisted of a tube and a solid insert, the dimensions being shown in Fig. 8. The tube was protected against rotating on an insert by stop screws (3). The assembly of the specimen elements maintained a fit ∅ 36 H7/h6. Both accepted elements to be tested (tube and insert) were made of extruded aluminium AlMgSi0.5. The material properties were: R_m=215 N/mm^2; $R_{p0.2}$=160 N/mm^2 and A_5=12%.

Over the entire test span the same tube element was maintained. At the same time, the contact surface of the insert was changed by grooves and patterns (knurling). As to identify the above mentioned important joining process phenomena, systematic test programmes have been elaborated [16]. As to induce the plastic deformation across the wall of the specimen tube, the tests envisaged two kinds of joining by external rolling:

– one-roller burnishing on a lathe (Fig. 8.),
– burnishing by a multi-roller head on a vertical drilling machine (Fig. 9).

The one-roller tool is presented in its working position in Fig. 8. It is a burnishing tool consisting of the rolling disk (∅ 40 mm, r=2.5 mm, α=2° 30′) made of tempered steel, the hardness being 64 HRC and which is mounted on a roller bearing. The rolling disk was pushed against the specimen by an internal spiral spring with a force of $F_n = 0.5 \div 1.5$kN.

Joining by rolling by use of a multi-roller burnishing head is presented in Fig. 9. The mentioned head (Type RA 3), which was manufactured by ECOROLL AG (Celle), was equipped with a fixed conical bearing track and 9

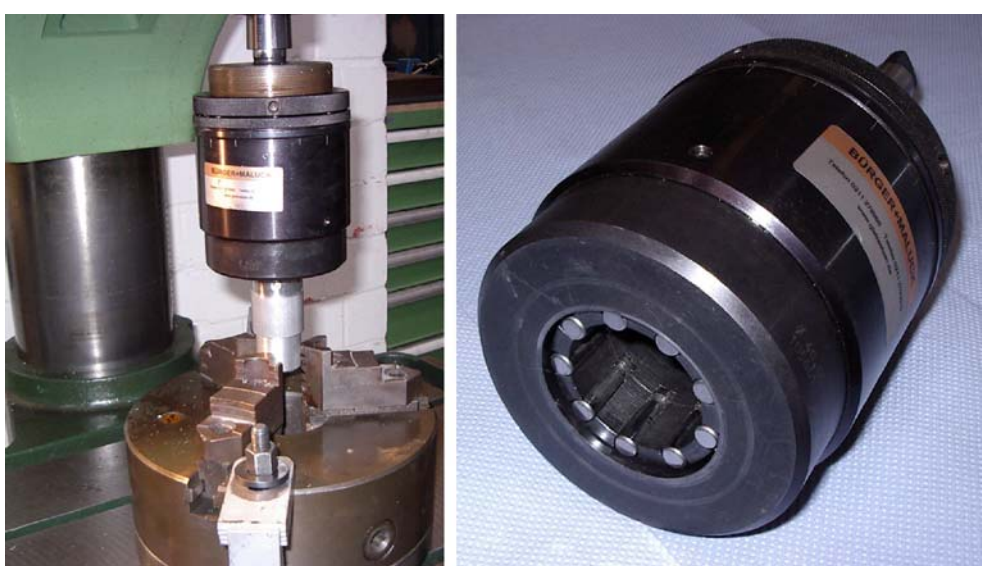
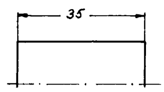
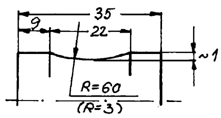
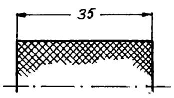
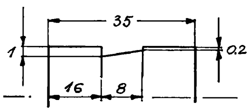
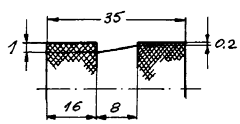
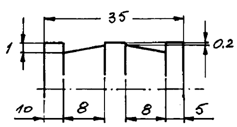
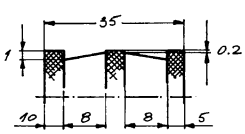


Fig. 9 Test specimen and multi-roller burnishing head in its working position on a vertical drilling machine

Table 1 Shapes of the insert contact surfaces

Code	Shape of the insert contact surfaces	Description
C		smooth (cylindrical)
R3 R60		rounded groove
KD		diamond knurled
T		trapezoid (dentil)
KD-T		diamond knurled + trapezoid (1 dentil)
2T		Double trapezoid (2 dentils)
KD-2T		diamond knurled + double trapezoid (2 dentils)

burnishing rollers ∅ 8×25 mm. The roller pressure induced into the surface of the specimen tube was produced by a rolling interference. Therefore, the adjusted diameter of the head was smaller than the one of the specimen tube by *s*-rolling oversize.

The glue which has been used for the chosen tests was the 3M scotch-weld epoxy structural adhesive type DP 490.

The research programme comprised tests leading to an estimation of the influence of rolling parameters and of the insert contact surface form on the joint resistance.

During the one-roller burnishing as presented in Fig. 8, the following parameters were applied: feed f=0.13 mm/rev. and rotational speed n=100 r.p.m. The feed f of the rolling tool was directed towards the spindle. When burnishing by the multi-roller head, as presented in Fig. 9, the working parameters were as follows: rolling feed f= 0.36 mm/rev., rolling oversize s=0.1 to 0.6 mm, and spindle speed n=100 r.p.m.

Shapes of the insert contact surfaces are shown in Table 1 and Fig. 10.

The joint disconnecting tests were performed on a ZWICK testing machine type 1475 by use of special testing equipment adapted by the authors to press the inserts out of the specimen tubes. The press-out speed was 10 mm/min. The test data was registered numerically and assessed by a Ms Excell programme.

5 Results of experiments

Using experimental digitised data obtained during the disconnection of the specimen joints, some of the characteristic charts are presented in Figs. 11, 12 ,13. They show the course of changes of disconnecting force during the test and can be used to assess the quality of joints.

Figure 11 indicates an evident influence of introducing surface formation by grooving and knurling on the joint resistance. The presence of two dentils is clearly indicated

Fig. 10 Set of inserts and a variety of their contact surfaces

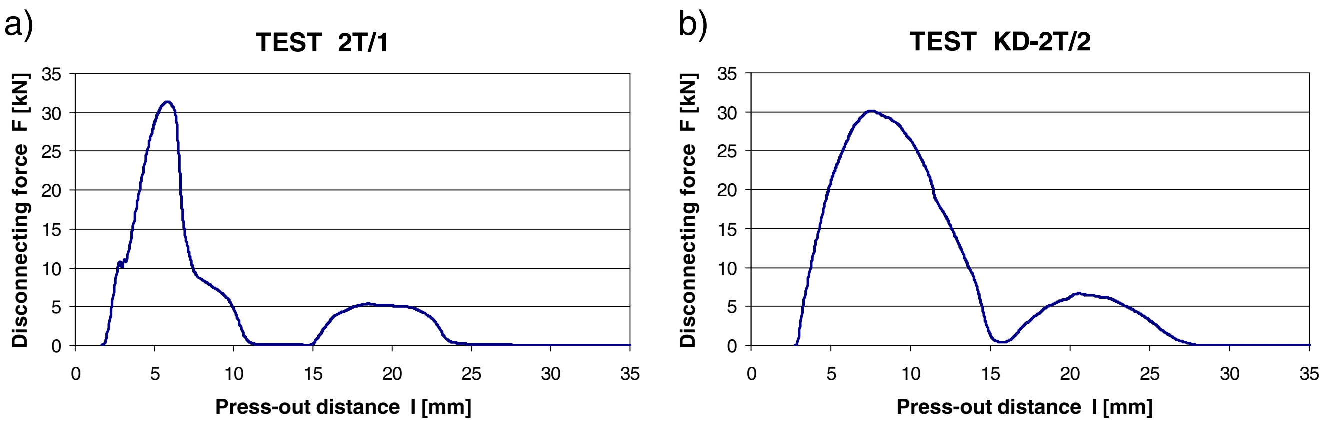


Fig. 11 Joint resistance influenced by dental grooving and knurling of the insert contact surface (one-roller burnishing): **a**) double trapezoidal grooving (2T), **b**) knurled and double trapezoidal grooving (KD-2T)

by two force peaks, the maximum one (disrupting force) being assumed as a joint resistance value equal app. 30 kN.

The graphs presented in Fig. 12 allow an analysis of the disconnecting force of the joint as being influenced by gluing, grooving, or knurling and enable a comparison of these factors. In the case of gluing, we can see a very high level of resistance equal to app. 40 kN and rapid disruption of the joint (Fig. 12a).

Similar phenomena appear in the first stage of disconnecting the glued joint in presence of knurling and grooving, but we can see additional supportive action of the joint surface formation (Figs. 12b and c). The strength is raised up to a value of about 50 KN. In the case of introducing the groove, the disconnecting force maintains a significant constant level over the length of the joint after disrupting the glue connection.

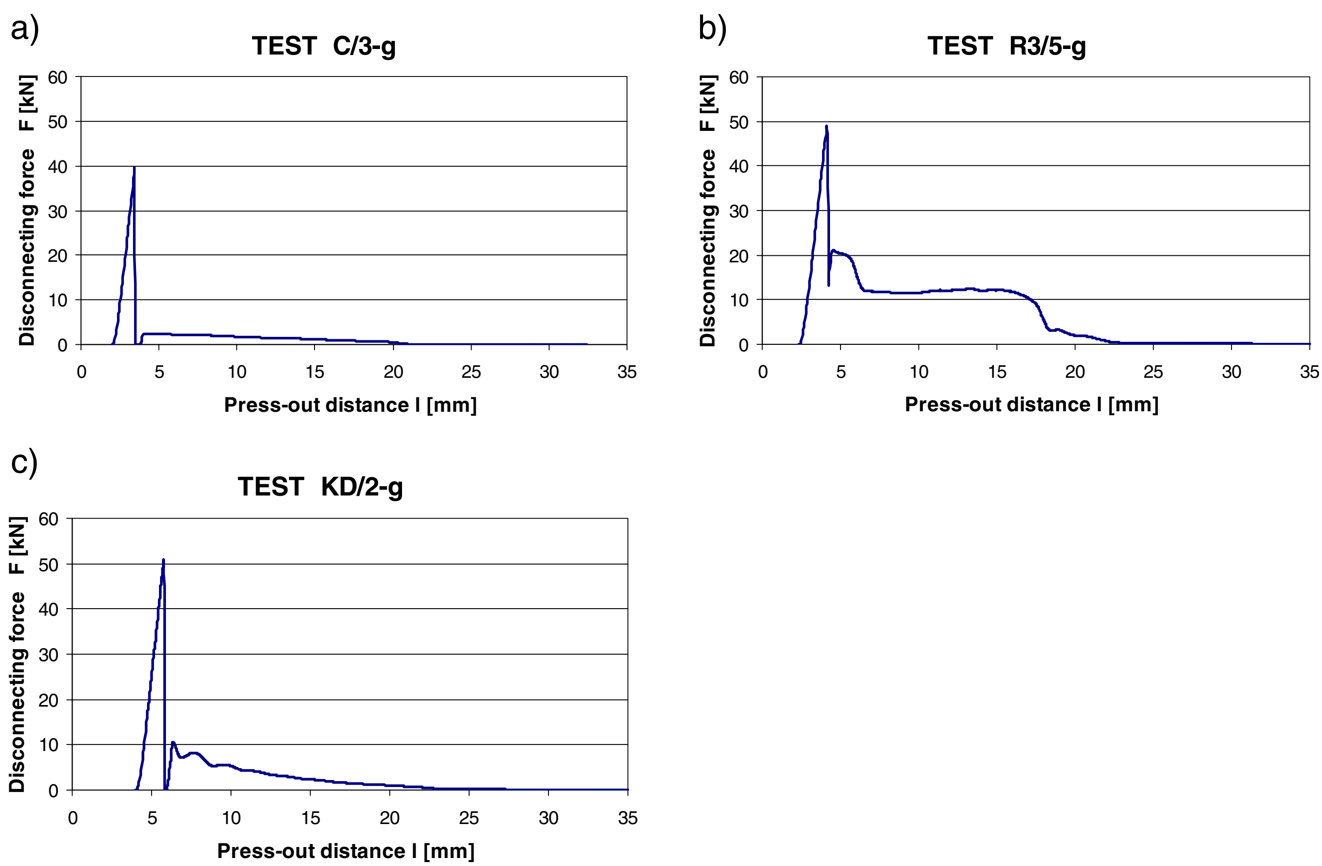


Fig. 12 Joint resistance influenced by gluing, radial grooving, and knurling of the insert contact surface (one-roller burnishing): **a**) cylindrical surface (C)-only glued and not burnished, **b**) radial grooving (R3) and gluing, **c**) knurling (KD) and gluing

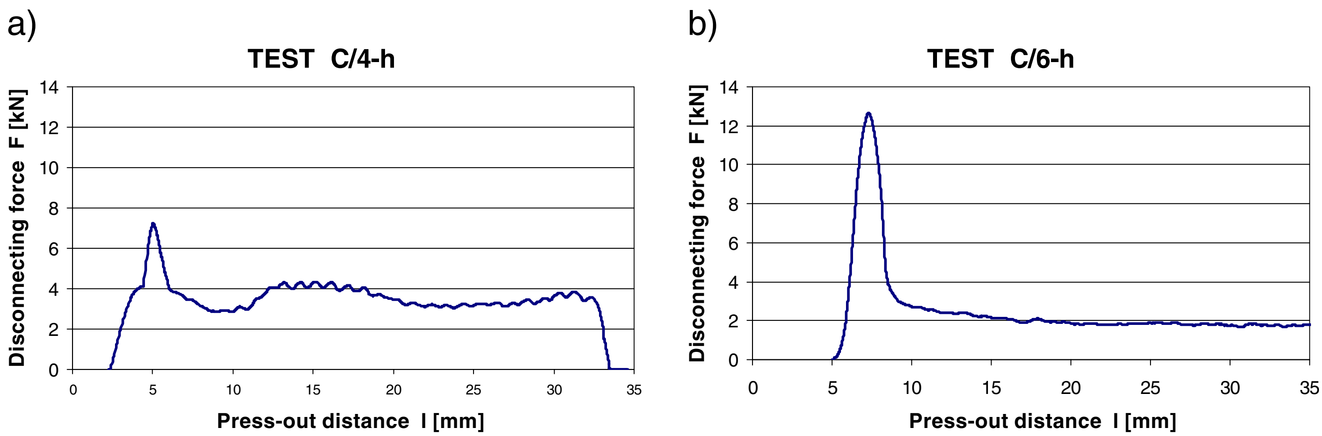


Fig. 13 Joint resistance influenced by the burnishing oversize s (multi-roller head): **a**) s=0.3 mm/rev. for cylindrical contact surface (C), **b**) s=0.48 mm/rev. for cylindrical contact surface (C)

Observations made on experimental graphs indicate that the higher the head rolling oversize ($s = 0.1 \div 0.6$mm), the higher the joint resistance (disconnecting force). For cylindrical specimens subjected to rolling keeping the rolling oversize 0.48 mm the force was F=12.6 kN (Fig. 13b) and for the same specimen, which was rolled keeping the oversize 0.3 mm, was only F=7.1 kN (Fig. 13a). When exceeding the value of s=0.48 mm, scaling of the outer surface appeared. This is due to excessive unit pressures applied to the tube.

In the case of burnishing by use of the multi-roller head, the joint resistance was higher than of those produced by one-roller burnishing. For the joint possessing inserts equipped with trapezoid groove (T), the disconnecting

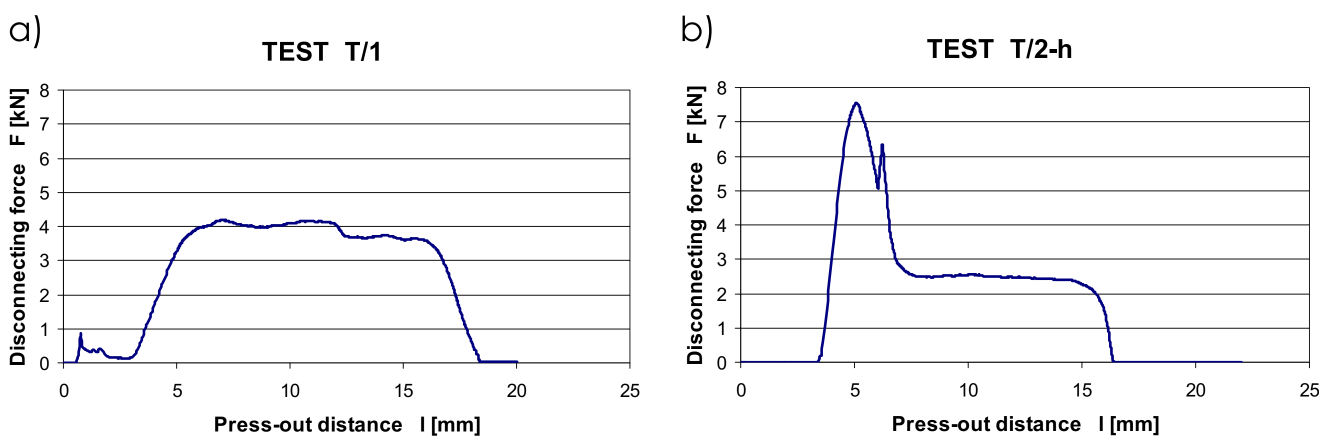


Fig. 14 Resistance of the joint equipped with trapezoid groove (T) as influenced by the rolling method: **a**) by a one-roller burnisher, **b**) by a multi-roller head

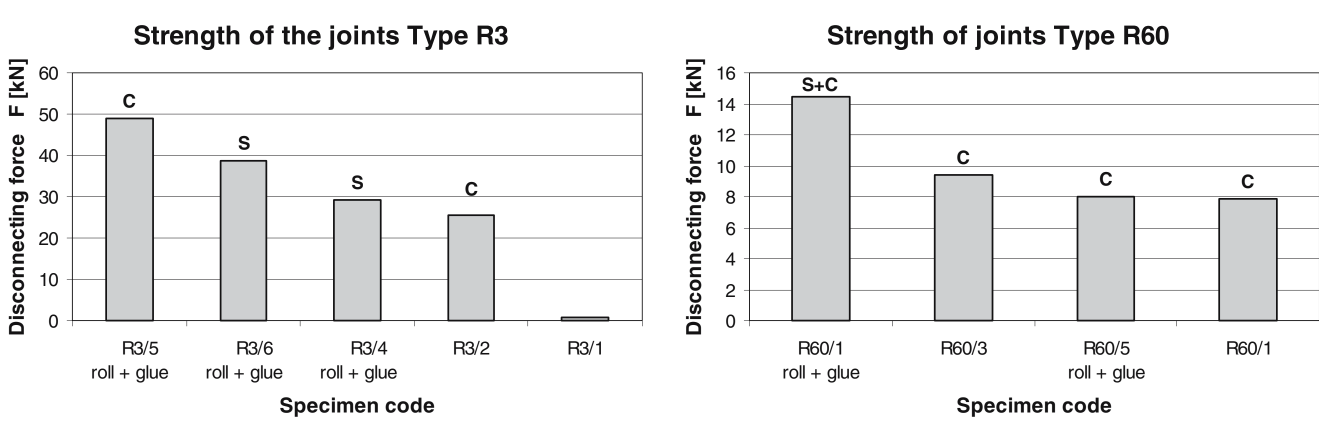


Fig. 15 Comparison of the disconnecting forces of joints Type R3 and R60 obtained by external rolling: S - straight-rolling; C - cross-rolling

Fig. 16 Cross-section of a cross-rolled joint Type R60

force equalled F=4.2 kN, wheras the resistance of the same type of joint burnished by a one-roller tool was F=7.55 kN (Fig. 14).

Figures 15 and 17 present a comparison of the disconnecting force of test specimens having different shapes of insert elements for different joining methods (direction of rolling and gluing).

The diagram presented in Fig. 15 proves that the rolled specimens which had narrower grooves (small radius R3) were more resistant than those equipped with wider ones. For example, the R3/2 specimen resisted the disconnecting force F=25.6 kN and the R60/3 specimen 9.41 kN respectively, maintaining the same cross-rolling parameters. The reason is that the narrow R3 groove in the insert is easier to fill-in by the outer tube material by use of the applied roller tool. The resulting indent collar increases the joint resistance. If the wide groove R60 is not totally filled-in, we can only obtain the sliding effect of the expanding outer ring over the groove length. In case of gluing, the effective gluing surface is reduced significantly. In Fig. 16, an interface gap can be seen.

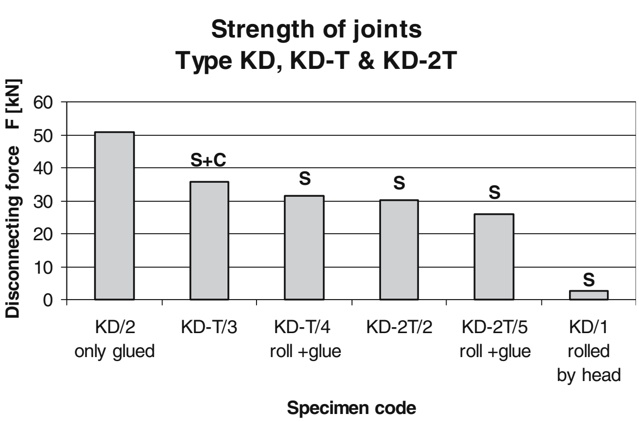


Fig. 17 Comparison of disconnecting forces of joints Type KD, KD-T & KD-2T obtained by external rolling: S - straight-rolling; C - cross-rolling

A comparison of different types of insert surfaces related to the disconnecting force by different rolling and gluing procedures is shown in Fig. 17. The best results were obtained by simple gluing (KD/2) amongst the glued cases and by combined cross and straight rolling amongst mechanical cases (KD-T/3).

Experiences gained in the course of the present research work showed that during rolling experiments the length of specimen tubes increased and at the same time the diameter went down. In the whole range of experiments on tubes ∅ 40×50 mm, the decrease of diameters equalled at least 0.1 mm with a corresponding elongation 0.3 mm. Observation was made that the higher the values of the rolling force F_n or of the rolling oversize s, the higher the specimen elongation and higher diameter reduction. Designers should consider this fact in practical use.

6 Conclusions

The tests, which were performed within the scope of the present research work, led to the following basic observations and conclusions:

- External rolling of joints type tube-insert in aluminium tubular structures appeared to be a promising technology for the manufacturing of resistant joints. In particular, it should be mentioned that a high quality joint can only be obtained by special insert formation by surface grooving or patterning.
- The grooved specimens subjected to rolling presented higher joint resistance compared with cylindrical ones. The best result can be obtained when the insert element is equipped with two trapezoid dentils (grooves). As a result of the present research work, the value of the joint resistance is F≅30 kN.
- External rolling of joints equipped with trapezoid-grooved insert elements using a multi-roller burnishing head gave better results than the one executed by a single-roller burnisher. In case of burnishing by a head, the joint resistance was 80% higher than the one produced by one-roller burnishing.
- The best results were obtained when the burnishing oversize was s=0.48 mm. Exceeding this value caused scaling and it can not be applied.

– Tubular joints where the glue is put on the grooved or patterned contact surface of an insert before rolling perform at about 27% higher resistance than the ones which were only glued. In the present research work, knurling supported gluing as to present the joint resistance after rolling $F \cong 50$ kN. At the same time, the simply glued cylindrical joint presented the strength $F=40$ kN.

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