INFLUENCE OF DESIGN CHARACTERISTICS AND MANUFACTURING PROCESS PARAMETERS ON THE STRENGTH OF TUBULAR ALUMINIUM JOINTS PRODUCED BY HYDROFORMING

Hydrobulging, which is one of the hydroforming techniques, appears to be an interesting method for the manufacturing of tubular joints. A special feature of this method is the lack of undesired heat effects, cleanness, and a quick joining procedure along with an easy implementation into practice. The basic incentive of the presented research work was to find out design and working conditions of producing resistant tubular joints by hydrobulging. The study comprised joining of specimen pairs type tube-ring. In the course of the research work different material combinations of the tube and the ring were tested, i.e. AA6060-AA6060, AA6060-AZ31, and AZ31-AA6060. Practical research was performed by testing the strength of the joint which was formed by hydrobulging. The research work was carried out on a special test stand which has been designed and manufactured at the Institute of Forming Technology and Lightweight Construction (University of Dortmund) within the scope of the Collaborative Research Centre TRANSREGIO 10, supported by the German Research Foundation (DFG).

Key words: lightweight structures, tubular joints, aluminium tubes, hydroforming

1. INTRODUCTION

Joining of tubular elements by expansion (bulging) presents an alternative to welding and screwing of joints. A special feature of this method is the lack of undesired heat effects, cleanness, and a quick joining procedure along with an easy implementation into practice. Tubular structures imply many important positive features (low weight and high resistance) and, therefore, they are commonly applied in a large variety of constructions, such as frames and cabs of...
automotive vehicles as well as roof structures, shields, rail-coaches, etc. (Fig. 1) [9]. The process of joining a shaft with a collar by expansion has been described in [1] and joining of profiles was first presented in [9]. At the same time, theoretical background may be found as well in [5, 6, 7].

When manufacturing aluminium tubular structures the following conventional processes are used: e.g. welding, screwing, and other methods producing permanent plastic deformations in the joining zone [3, 4, 10]. The methods fulfilling this condition are: electromagnetic compression, hydrobulging, explosive joining, and rolling [8, 10, 11].

The present paper deals with research work performed by the authors at the Institute of Forming Technology and Lightweight Construction (Universität Dortmund) within the scope of the Collaborative Research Centre TRANSREGIO 10, supported by the German Research Foundation (DFG). The subsequent sections of the report present the research work regarding the process of producing tubular joints (tube-ring) by expanding (hydrobulging) the internal tube made of aluminium AA6060 F22 and magnesium AZ31 in order to join it with the outer ring made of aluminium AA6060 F25 and magnesium AZ31, both elements being coupled in a different combination of materials.
Hydrobulging, which is one of the hydroforming techniques, appears to be an interesting method for the manufacturing of tubular joints. Unlike in an ordinary interference fit joint there is an initial clearance between the tube and the ring or another outer element. In case of steel elements the tube is inserted into the ring with a clearance \( g = D_i - d_o = 0.05 \text{ mm up to } 0.2 \text{ mm and joint diameters } \varnothing 22 \text{ mm up to } \varnothing 30 \text{ mm} \ [5].

The working hydro-insert is introduced into the tube and the hydro-medium under pressure \( p_f \) is directed into the gap between the hydro-insert and the inner surface of the tube. At the same time, o-rings close the space (hydro-chamber) and limit the length of the joint interface (Fig. 2b).

In the first phase the tube expands within the clearance (gap) limit and then both parts (tube-ring) expand together up to the maximal joining pressure (Fig. 2a–b). After releasing the pressure down to \( p_f = 0 \) the tube-ring element springs back elastically and maintains the plastic deformation produced during the bulging operation (Fig. 2c).

The effective and resistant joint will be produced only in compliance with certain conditions related to the material properties of the joint elements (tube-ring). As tested for steel elements of the joint, the material of the inner element (tube) has a significantly lower yield point level than the one of the outer element (ring). The tube will be plastically deformed, whereas the ring remains within the elastic deformation state and the interference fit state appears in the joint. Results obtained for steel [1, 2] allow the assumption that other joint materials like aluminium rings and tubes can also be effectively joined by hydroforming.

Stress-strain curves presented in Fig. 3 show how different material properties of the joint elements influence the joint quality (strength) [5].
Curves shown in Fig. 3a illustrate the joining process of materials of the same elasticity modulus. After overcoming the clearance $\varepsilon_{g}$ the bulging effect starts by a simultaneous expansion of the tube and ring up to the yield point of the ring. Both elements spring back after releasing the pressure, which occurs parallel to the Hook’s curve by the value $\varepsilon_{\text{back}}$. Finally, the remaining tensile stress in the ring produces the interference fit by created interference fit pressure $p$ in the contact zone between the tube and the ring in radial direction. If the yield point of the ring material would be higher, interference fit pressure $p$ would be higher.
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too (Fig. 3b). Choosing reversed material properties of joint elements, i.e., a lower yield point of the ring than the one of the tube, will result in a lack of joining effects (Fig. 3c).

From the engineering point of view the working parameters of the fluid pressure $p_f$ present an important estimation target. According to research work performed by Garzke [5], the values of interference pressures $p$ can be approximately estimated by calculations. The corresponding formula (1), which takes into account the influence of the mentioned working fluid pressure along with material design characteristics and material properties, is as follows:

$$p = \frac{\left[p_f - R_{ei} \cdot \ln\left(\frac{1}{Q_i}\right)\right] \cdot \frac{1}{E_o} \cdot \left[\frac{1+Q_o^2}{1-Q_o^2} + v_o\right] + \frac{2 \cdot Q^2}{E_i \left(1-Q^2\right)} \cdot R_{ei} \cdot \ln(Q_i)}{\frac{1}{E_o} \cdot \left[\frac{1+Q_o^2}{1-Q_o^2} + v_o\right] + \frac{1}{E_i} \cdot \left[\frac{1+Q^2}{1-Q^2} - v_i\right]},$$

(1)

$p$ – interference pressure \([\text{N/mm}^2]\),

$p_f$ – working fluid pressure \([\text{N/mm}^2]\),

$R_{ei}$ – elastic limit of the tube material \([\text{N/mm}^2]\),

$E_i$ – modulus of elasticity of the tube material \([\text{N/mm}^2]\),

$E_o$ – modulus of elasticity of the ring material \([\text{N/mm}^2]\),

$v_i$ – Poisson’s ratio of the tube material,

$v_o$ – Poisson’s ratio of the ring material,

$Q_i$ – diameter coefficient of the tube where $Q_i = d_i/d_o$ (see Fig. 4),

$Q_o$ – diameter coefficient of the ring where $Q_o = D_i/D_o$ (see Fig. 4).

3. TARGET SETTING AND EXPERIMENTS

The basic interest of the presented research work was to find out design and working conditions of producing resistant tubular joints by hydrobulging. The study comprised joining of specimen pairs type tube-ring. In the course of the research work different material combinations of the tube and the ring were tested, i.e. Al-Al, Al-Mg, and Mg-Al. Practical research was performed by testing the strength of the joint which was formed by hydrobulging. The aim of the tests was to determine the influence of the major geometrical factor $Q_o$, which was examined by varying the thickness of the ring $t_o$ (Fig. 4) along with the process parameters (expansion) influencing the strength of the joint. For test purposes AA6060 F22 and F25 aluminium (AlMgSi0.5) as well as AZ31 magnesium (MgAl3Zn1) elements were used. The dimensions of the joined inner tubes (AA F22 and AZ31) were $\varnothing 40 \times 2$ mm. AA6060 F22 (F25) properties were in acc. with DIN 1748: $R_m = 245$ N/mm$^2$ ($R_m = 215$ N/mm$^2$); $R_{p 0.2} = 195$ N/mm$^2$ ($R_{p 0.2} = 160$ N/mm$^2$);
$A_s = 10\% \ (A_5 = 12\%)$. AZ31 properties were in acc. with DIN 9711 where: $R_{p0.2} = 175 \text{ N/mm}^2$; $A_5 = 10\% \ (A_5 = 20.5\%)$. For test purposes the tube-ring specimens were set together (Fig. 4) maintaining different values of clearance ($g$) and the same surface roughness.

![Fig. 4. View of the specimen construction for tests of tensile strength of the tubular joint: 1 – tube, 2 – ring, 3 – working hydro-insert, 4 & 5 – sealing rings](image)

As to achieve the target objectives the research plan envisaged testing the following influencing factors:
- wall thickness of the ring $t_o$ : 2, 5, 8, 9.5 mm,
- diameter clearance $g$: 0.1, 0.2, 0.3 mm,
- tube-ring material combination: AA6060 F22-AA6060 F25, AA6060 F22-AZ31, AZ31-AA6060 F25, AZ31-AZ31,
- expansion value $\Delta D_o$: 0.1, 0.3, 0.4, 0.6, 0.9, 1.0, 1.1, 1.2, 1.3 mm, constant factors being the diameter ($d_o = \phi 40$ mm) and wall thickness ($t_i = 2$ mm) of the tube.

The specimen surfaces were carefully degreased before assembling in order to eliminate any additional side effects on the test results.

The following research work plan was elaborated:
- **AA6060 F22-AA6060 F25** – tube and ring made of aluminium
  a) $F = f(\Delta D_o); t_o = 5 \text{ mm}, l = 32, g = 0.2 \text{ mm, } \Delta D_o = 0.1, 0.3, 0.4, 1.0, 1.4 \text{ mm,}$
  b) $F = f(g) t_o = 5 \text{ mm}, l = 32, g = 0.1, 0.2, 0.3 \text{ mm, } \Delta D_o = 1.0 \text{ mm,}$
  c) $F = f(t_o) t_o : 2, 5, 8, 9.5 \text{ mm}, l = 32, g = 0.2 \text{ mm, } \Delta D_o = 0.4 \text{ mm,}$
  d) repeatability tests for constant parameters (7 tests) $t_o = 5 \text{ mm, } l = 32 \text{ mm, } g = 0.2 \text{ mm, } \Delta D_o = 0.4 \text{ mm,}$
- **AZ31-AZ31** – tube and ring made of magnesium
a) \( F = f(\Delta D_o) \); \( t_o = 5 \text{ mm}, l = 32, g = 0.2 \text{ mm}, \Delta D_o = 0.4, 0.6, 0.9, 1.0, 1.1, 1.2, 1.3 \text{ mm}, \)

b) \( F = f(g) \); \( t_o = 5 \text{ mm}, l = 32, g = 0.1, 0.2, 0.3 \text{ mm}, \Delta D_o = 1.2 \text{ mm}, \)

c) \( F = f(t_o) \); \( t_o : 2, 5, 8, 9.5 \text{ mm}, l = 32, g = 0.2 \text{ mm}, \Delta D_o = 1.2 \text{ mm}, \)

– Different materials of the joint couples (tube ring)
a) AA6060 F22-AZ31
\( t_o = 2 \text{ and 9.5 mm}, l = 32 \text{ mm} g = 0.2 \text{ mm}, \Delta D_o = 0.4 \text{ mm}, \)
b) AZ31-AA6060 F25
\( t_o = 2 \text{ and 9.5 mm}, l = 32 \text{ mm} g = 0.2 \text{ mm}, \Delta D_o = 0.4 \text{ mm}. \)

In the present research work, joining by hydrobulging was performed on a special test stand which has been designed and manufactured at the Institute of Forming Technology and Lightweight Construction (Universität Dortmund). Fig. 5 shows the cross section of the stand in its working state. It is powered by a hydro-medium (water), fed by a three-step pressure intensifier MAXIMATOR with a pressure of up to max. 4000 bar. As shown in Fig. 5, the specimen consisting of the tube (1) and the ring (3) was axially aligned with the use of a special ring supported by 6 radial spring pressing elements.

![Test stand for hydrobulging](image)

Fig. 5. Test stand for hydrobulging of tubular joints: 1 – tube, 2 – working hydro-insert, 3 – ring, 4 – centring flange, 5 – centring pin, 6 – displacement transducer, 7 – guiding columns, 8 – hydro-medium supply

Rys. 5. Fragment stanowiska do wytwarzania złącz metodą hydrorozpęczania: 1 – rura, 2 – hydrauliczny trzpień rozpęczający, 3 – pierścień, 4 – kolnerz ustalający, 5 – kółko ustalające, 6 – czujnik przemieszczeń, 7 – kolumny prowadzące, 8 – ciecz robocza

After its positioning, the working hydro-insert (2), which can also be seen in Fig. 6, was introduced into the tube. The tool was fed by a hydro-medium supplied by a high-pressure pipe from the pressure intensifier.
Fig. 6. Working hydro-inserts
Rys. 6. Hydrauliczne trzpienie rozpęczające

Fig. 7. Extraction test equipment used on the tensile test machine Zwick 1475: a) special equipment; 1 – upper coupling collar, 2 – specimen, 3 – frame, 4 – specimen seat, 5 – deformation security ring, 6 – gripping segments, 7 – blocking nut, 8 – tightening rod, 9 – lower coupling collar; b) scheme of extrusion tests
Rys. 7. Układ roboczy strefy rozłączania próbek na maszynie wytrzymałościowej Zwick 1475: a) oprzyrządowanie specjalne; 1 – kółnik górny, 2 – próbka, 3 – rama, 4 – gniazdo próbki, 5 – pierścień zabezpieczający przed odkształceniem rury, 6 – segmenty trzpienia mocującego, 7 – nakrętka blokująca, 8 – trzpień, 9 – kółnik dolny; b) schemat rozłączania siłą osiową
The position of the working hydro-insert inside the tube of the specimen was set by special templates. The expansion $\delta_p$ of the outer diameter $D_o$ of the ring was measured by two oppositely located displacement transducers (6) and was recorded. A special electronic device enabled the monitoring and recording of the pressure levels in the bulging zone (chamber) and the calculation of real $\delta_p$ values for each tested specimen.

Special care was put to an initial cleaning of the interface surface and the one of the outside diameter of the tube as well as of the inner surface of the ring. All remaining chip particles and grease were washed out by a solvent.

The disconnecting tests were performed on a ZWICK tensile test machine type 1475 by use of special test equipment adapted to disconnecting joints type tube-ring and which are presented in Fig. 7 [10]. The extraction speed was 10 mm/min.

The disconnecting tests, which were performed on a tensile test machine and are described above, were subjected to a registration in a numerical and graphical form. From the graphs’ changes of the disconnecting force $F$ vs. the extraction length of the joint the disruption force $F_d$ could be read. At the same time, a seizing effect was monitored and registered as seizing force $F_s$.

The specimen tube was extracted from the ring until the joint was fully disengaged. Consequently, force changes could be analysed on the full disconnecting distance.

### 4. TEST RESULTS AND DISCUSSION

The registered test results were subjected to a comparative analysis. Below, some of the chosen and typical graphs are presented.

Fig. 8 shows graphs illustrating changes of the disrupting forces $F$ of an aluminium AA6060 joint along the extraction distance $l$ for two different expansions $\Delta D_o$ of the outer ring. Evidently, a different character of the graphs can be seen. In case of a small value of $\Delta D_o = 0.1$ mm (Fig. 8a) the disconnecting force $F$ increases up to the disrupting force $F_d$ in order to fall down rapidly afterwards. Then the force $F$ constantly decreases until a full disengagement of the joint elements. For a level of $\Delta D_o = 1$ mm (Fig. 8b) the graph presents different characteristics. After the disrupting force $F_d$ is reached a small force drop can be observed, followed by a significant force raise up to the second maximum value $F_s$ after which a constant force drop follows until a full disengagement of the joint elements. The mentioned phenomena occur due to the seizing effect on the joint interface.
A similar comparison made for AZ31 joints shows that only the second graph type exists (Fig. 9), the seizing forces \( F_s \) being several times higher than the initial disrupting forces \( F_d \). It can be concluded that magnesium AZ31 joints reveal a much higher seizing tendency than those of aluminium AA6060 ones. At the same time, much lower force levels are obtained.

The disrupting force \( F_d \) is influenced by design characteristics of the joint: material, length \( l \), and thickness \( t_o \) of the ring along with the working parameters of the manufacturing operation, which is expansion \( \Delta D_o \) of the outer ring. Fig. 10 presents the influence of the clearance \( g \) on the disrupting force \( F_d \), which decreases when the clearance \( g \) decreases (Fig. 10). If clearance \( g \) is increased, a larger necessary plastic deformation of the tube is needed to fill the initial gap between tube and ring before the simultaneous expansion proceeds.

Consequently, as indicated in Fig. 3, an increased \( e_{gap} \) determines a larger total elastic ratio of the tube until the end of the expansion process. As a consequence, the total elastic spring-back of the tube is increased, causing a minor interference pressure \( p \) which, therefore, leads to a lower extraction force \( F_d \) (1).

Fig. 11 presents the influence of the ring thickness \( t_o \) on the disrupting force \( F_d \) for two different joint materials and which, in both cases, increases up to app. 15 kN for AA6060-made joint elements (Fig. 11a) and only to 1.6 kN for AZ31-made joint elements (Fig. 11b). As proved in former research work [11] and qualitatively conforming with results of (1), the practically effective influence of the ring wall thickness can be observed up to \( t_o = 8÷10 \) mm and, having in view the joint lightweight aspect, it seems unreasonable to go beyond the wall thickness of \( t_o = 10 \) mm.
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a) $F_d = 0.6$

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b) $F_d = 0.7$

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Fig. 9. Joint disconnecting forces $F$ as influenced by the bulging extent $\Delta D_o$ for ring and tube material AZ31: a) $\Delta D_o = 0.6$ mm, b) $\Delta D_o = 1.2$ mm; characteristics of the joint – $l = 32$ mm, $t_o = 5$ mm, $g = 0.2$ mm

Rys. 9. Wpływ stopnia rozpadnięcia ($\Delta D_o$) złącza rura–pierścień z materiału AZ31 wykonanego metodą hydroformingu na przebieg sił rozłączających $F$: a) $\Delta D_o = 0.6$ mm, b) $\Delta D_o = 1.2$ mm; charakterystyka złącza – $l = 32$ mm, $t_o = 5$ mm, $g = 0.2$ mm

The graphs shown in Fig. 12 present a comparison of the disrupting force $F_d$ as influenced by the working parameter $\Delta D_o$ and by the ring thickness $t_o$ for different materials of the joint partners.

The relation $F_d = f(\Delta D_o)$ shown in Fig. 12a where the pairs ring-tube were made of the same materials, i.e. AA6060-AA6060 and AZ31-AZ31, reveals an extremely high difference between the disrupting forces for those different materials of the joints from app. 1 kN for magnesium type AZ31 to app. 12 kN for aluminium AA6060. A similarly contrasting strength resistance of the joints was observed when testing different ring thicknesses $t_o = 2$ mm and $t_o = 9.5$ mm (Fig. 12b). In both cases AZ31 joints presented a poor performance by extremely low disrupting forces and can not be recommended to be produced by hydrobulging.
Fig. 11. Joint disrupting forces $F_d$ as influenced by the wall thickness of the ring $t_o$ in a joint produced by hydroforming for different materials of joint elements: a) $\Delta D_o = 0.4$ mm, joint material – AA6060, b) $\Delta D_o = 1.2$ mm, joint material – AZ31; characteristics of the joint – $l = 32$ mm, $g = 0.2$ mm

A final assessment of the test results was slightly disturbed by the fact that setting up consistent expansion values $\Delta D_o$ was difficult to perform by the pressure tuning on the test stand and, hence, the changes of $F_d$ values in 7-specimen repeatability tests ranged between 11.92–13.68 kN (Fig. 13).

The mentioned test was performed in constant design and working conditions, i.e. $\Delta D_o = 0.4$ mm, $g = 0.2$ mm, $t_o = 5$ mm, $l = 32$ mm, material of the joint being AA6060. At the same time the corresponding fluid pressure was measured and, along with other design parameters of the joint introduced into the formula (1) as to calculate the theoretical interference pressure and the expected disrupting force of the joint.

The values obtained by calculation for the mentioned AA6060 joint were: $p = 19.4$ N/mm$^2$ and $F_d = p \pi d_o l \mu = 19.4 \pi 40 \cdot 32 \cdot 0.2 = 15,600$ N = 15.6 kN the specimen characteristics and test conditions were as follows: $p_f = 67$ N/mm$^2$, $Q_i = d_i/d_o = 0.9$, $Q_o = D_i/D_o = 0.8$, $R_ei = 90$ N/mm$^2$, $E_i = E_o = 69,500$ N/mm$^2$, $v_i = v_o = 0.33$.

Differences between the calculated disrupting force (15.6 kN) and force obtained in practice (app. 12 kN) can be explained by the fact that the formula (1) was elaborated by Garzke [5] for steel joint partners. Furthermore, different friction coefficient for aluminium and side supporting effects of the ring hole extremities play a certain role. In case of aluminium AA6060 corrective coefficients should be added which will envisage real friction conditions and values for aluminium couples.
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Fig. 12. Joint disrupting forces $F_d$ as influenced by expansion $\Delta D_o$ and wall thickness of the ring $t_o$ for different materials of joint elements: a) $F_d = f(\Delta D_o)$ ring and tube being made of the same material, b) comparison of disrupting forces $F_d$ for different wall thickness of the ring $t_o$ (specimens materials: AZ31 tube & AA6060 F25 ring or AA6060 F22 tube & AZ31 ring); characteristics of all joints – $l = 32$ mm, $t_o = 5$ mm, $g = 0.2$ mm

Rys. 12. Wpływ wielkości rozruchania $\Delta D_o$ oraz grubości ścianki pierścienia $t_o$ na siłę naruszającą stabilność złącza $F_d$ dla różnych materiałów jego elementów: a) $F_d = f(\Delta D_o)$ dla pierścienia i rury wykonanych z tego samego materiału, b) porównanie sił naruszających stabilność złącza $F_d$ dla różnych grubości pierścienia $t_o$ (materiały skojarzenia elementów złącza: AZ31 rura i AA6060 F25 pierścien lub AA6060 F22 rura i AZ31 pierścien); charakterystyka wszystkich złączy – $l = 32$ mm, $t_o = 5$ mm, $g = 0.2$ mm

Fig. 13. Disrupting forces $F_d$ and expansion $\Delta D_o$ in repeatability test for AA6060 aluminium specimens produced by hydrobulging maintaining constant characteristics of all joints: $g = 0.2$ mm, $t_o = 5$ mm, $l = 32$ mm

Rys. 13. Test powtarzalności wyników badania siły $F_d$ i rozruchania $\Delta D_o$ dla złączy z materiału AA6060 wykonanych metodą hydroformingu w tych samych warunkach: $g = 0.2$ mm, $t_o = 5$ mm, $l = 32$ mm
5. CONCLUDING REMARKS

The experiments which were performed within the scope of the presented research work can be concluded as follows:

– The hydrobulging method enables the production of aluminium tubular force-fit joints type tube-ring which can be applied in industrial practice, whereas joints made of AA6060 can resist an axial force of up to $F_d \approx 15$ kN (approx. 50% of the AA6060 tube tensile force) as the AZ31-made joints enable achieving not more than $F_d \approx 1.7$ kN.

– The disconnecting force $F$ is influenced by the following basic factors: type of material, thickness $t_o$, and length $l$ of the ring as well as expansion $\Delta D_o$ of the ring and assembly clearance $g$ on the tube-ring interface.

– It can be observed that for aluminium joints the disrupting force $F_d$ increases with an increase of the wall thickness of the ring. Taking into account the joint lightweight aspect it is advisable not to go beyond a wall thickness of $t_o = 10$ mm.

– The force $F_d$ decreases along with an increase of the clearance $g$. Additionally, the observation was made that the force $F_d$ increases for increasing values of expansion $\Delta D_o$ only up to 0.4 mm and then, for $\Delta D_o = 0.4$ to 1.5 mm, it slightly decreases. For the tested joint characteristics it is advisable to apply $\Delta D_o = 0.4$ mm.

– In case of producing joint couples made of different materials it seemed that the joint couple AA6060 F22 (tube) and AZ31 (ring) was more resistant than in the reverse case (AZ31-AA6060 F25). In the first case and for the ring wall thickness $t_o = 9.5$ mm the disrupting force was $F_d = 10.3$ kN and in the second case it was only $F_d = 0.4$ kN.

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Recenzent: dr hab. inż. Jan Materniak

WPŁYW PARAMETRÓW KONSTRUKCYJNYCH RUROWYCH ZŁĄCZY ALUMINIOWYCH ORAZ TECHNOLOGII ICH WYTWARZANIA METODĄ HYDROFORMOWANIA NA ICH WYTRZYMAŁOŚĆ

Streszczenie


Słowa kluczowe: konstrukcje lekkie, złącza rurowe, rury aluminiowe, hydroformowanie