APPLICATION OF COMPLEX MICRO-DIE FOR EXTRUSION OF MICRO-RIVETS FOR MICRO-JOINING

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Abstract

One of the modern industry trends is to be able to manufacture components of relatively small size using traditional or new technologies. Smaller components usually need special assembly techniques. New course of mechanical joining improvement is to develop process modification for decreased scale, i.e. micro-joining. The development of micro-joining: micro-self-piercing riveting (M-SPR) and micro-clinching (M-C), require designing special tooling and, in case of the M-SPR, the development of production technology of micro-rivets (M-rivets). Rivet production by forming produces certain distribution of stress/strain field within cross-section of a rivet, influencing the process of SPR joint formation in micro-joining. Stress/strain field obtained during rivet production is taken into account in numerical simulation of micro-riveting process. Initial assumption was to make joints with dimensions less than 1mm. Both, the process of preforms for M-rivets and forming of M-rivet are proposed and verified by either numerical and experimental analysis.

Keywords: Micro-extrusion, micro-joining, micro-rivets, numerical modeling

1. MECHANICAL MICRO-JOINING

One of the main development directions of the industry is to manufacture small dimensions components with either modified traditional or new technologies. Production of micro-devices demands adaptation of assembly methods, including separated parts joining. New development direction of mechanical joining techniques is such modification to adopt for micro-joining. One of the most intensively expanded mechanical joining methods of sheets are self-piercing riveting (SPR) and clinching. The SPR process has been described in several works, eg. [1-4]. It can be described as a continuous cold forming operation in which the rivet during setting pierces top layer(s) and forms a permanent mechanical interlock as a combination of positive and non-positive locking within two or more layers of material. It seems that the application of this method for the micro-joining could be very promising. Although the process seem to be more complicated than clinching, because of use of additional element - rivet, it offers noticeably higher joint strength. Thus, it looks that trial of adaptation of the SPR for micro-joining is worth consideration.

Generally, to get a joint by means of the SPR, the rivet must penetrate the upper layer(s) and then deform plastically while driving into the lower layer, without piercing it, **Figure 1**. Initial plan with the concept of micro-self-piercing riveting (M-SPR) process development was to make joints with dimensions in the range between 1 - 0.5 mm. Decreasing the SPR process components size - tools, rivet, sheets - below 1 mm must have influence on the process design. Based on the authors experience supported by research in the field of micro-forming, technological difficulties accompanying the proper filling of the micro-die, both in the manufacture of micro-rivet and in the process of micro-joining, apart from general difficulties with manipulation of the process components, must be taken into account.

2. MICRO-RIVET MANUFACTURING PROCESS PROPOSAL

Standard shapes of "macro" rivets in case of developing technology for M-Rivets inclined to use micro-extrusion process - sequence of operations were indicated by the results of numerical simulation in conjunction with experimental attempts.

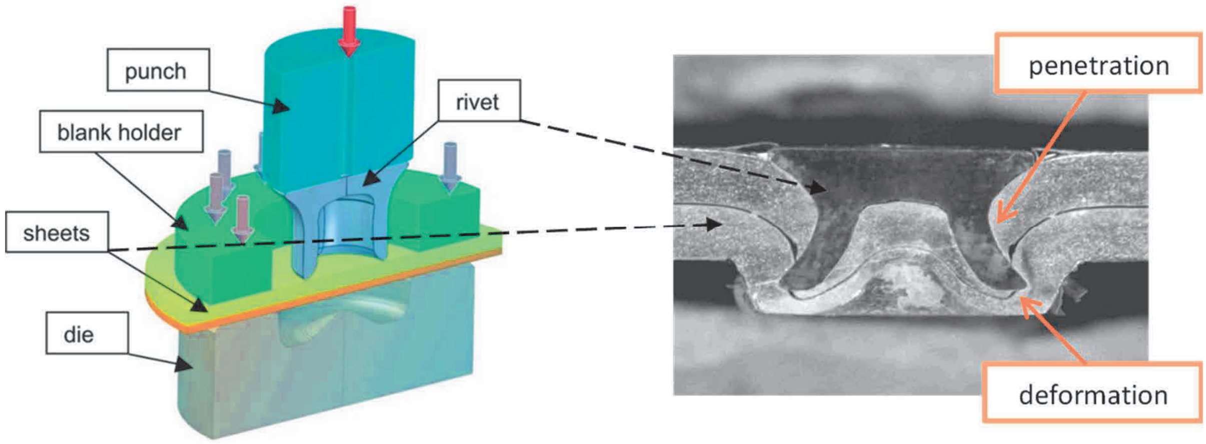


Figure 1 Outline of the standard SPR process and example of the SPR joint cross section

Open question was related with the ability to control not only the shape of the component (M-rivet), but also its properties - rivet must be appropriately strengthened during forming, which is very important in macro-joining. A separate issue in M-Rivet extrusion was to manufacture the appropriate preforms. It was planned to obtain preforms in a process consisting of micro-blanking, using a blankholder and ejector, and compression in a cylindrical die. An issue requiring special interest in design technology of M-Rivet manufacturing is to obtain a sufficiently dimensional accuracy and appropriate sharpness, equality of edges of the product and the suitable surface roughness. With respect to micro-components made from conventional materials, these characteristics are often difficult to obtain.

Based on a review of industrial applications of the SPR and own research related with this technique on the macro scale [3-4], there was selected the most widely used shape of the rivet, which is the base geometry for the study of M-Riveting, **Figure 2.** Also the die profile geometry was proposed according to applied rivet shape. Selected rivet dimensions were scaled assuming that the largest dimension of the rivet (outer diameter of the head) will be 1mm.

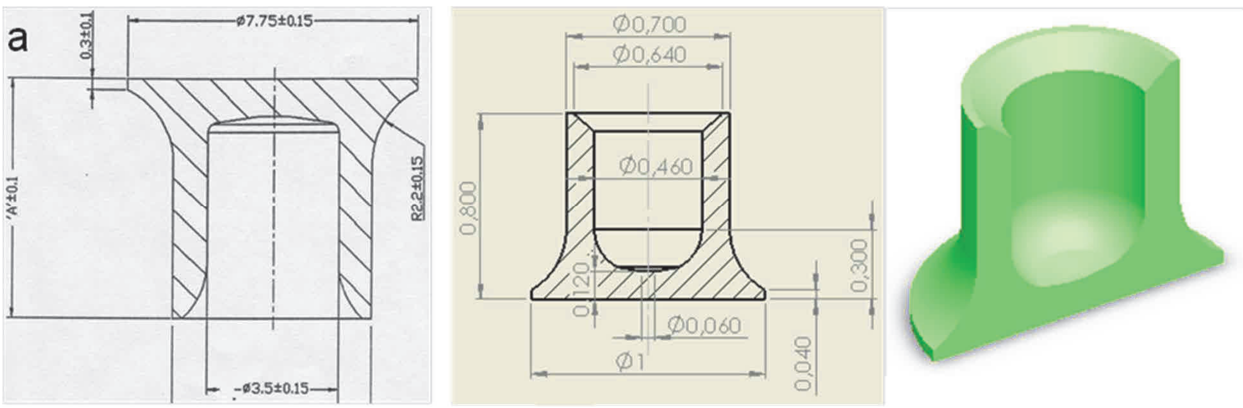


Figure 2 Rivet dimensions scaling idea: a - dimensions of the conventional rivet (macro), b - dimensions of rescaled rived (M-Rivet), c - 3D M-Rivet model

Scaling any metal forming process to micro-dimensions is accompanied with problems related with the similarity theory, commonly known as - so-called - structural and contact effects of scaling [5-7]. At this stage, they have not been taken into account directly, but as a consequence of micro-scale significantly higher coefficient of friction has been involved.Usually preforms obtained after metal forming require appropriate secondary operations, such as evening certain surfaces or correction of dimensions. In the present case, is was assumed that the resulting shape of the M-Rivet will be final. For practical reasons, in analyzed case of M-Rivet forming, it seemed to be the best solution, to set all operations in a dedicated tool, using specially designed micro-tools.

Basing on the standard recommendations, supported by numerical modeling, two modifications of M-Rivet micro-extrusion process were designed. The proposed solutions used two deformation patterns shown in **Figure 3** - process I and process II. It was assumed that the micro-preforms would be manufactured by micro-blanking. For this purpose previously proposed concept of the CMEX process (Complex Micro-Extrusion) [8] was implemented. It should be noted that in the "macro-forming technology" such a method of preforms manufacturing is not used. Taking into account the shape (not the size) of the preform, it would be rather machining or cutting applied. The main reason for the use of micro-blanking preforms was just preform ,,micro-size".

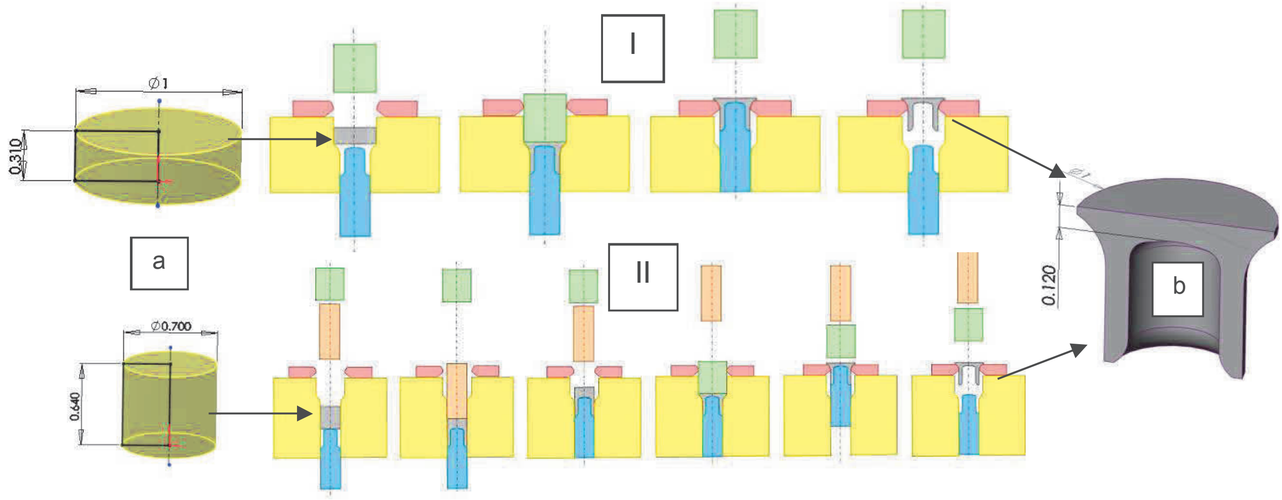


Figure 3 A concept of two M-rivet extrusion I and II: the dimensions of the preforms (a), process diagram and assumed the shape of M-rivet after forming (b)

Process I consits of: insertion of the cylindrical preform into the die, forward extrusion with flat punch over convex counter-punch (rod of diameter d_z=0.7 mm, cup of inner diameter d_w = 0.46 mm), last stage M-Rivet head upsetting, flat punch withdrawal, M-Rivet ejection with counter-punch beyond die zone, approaching divided puller, counter-punch withdrawal, M-Rivert removal from the puller hole. The process II is generally different by the upsetting of the M-Rivet head is splitted in two attempts. As it is shown in the figures, the application of variable punches system with the same die provides another path of the material flow, and consequently, a different strain distribution in M-rivet. It is already known for macro-scale SPR, eg. [3-4], that the stress state, or more precisely, the values and distribution of the yield stress, affects the quality of the final joint. This should be understood as a more or less optimal rivet deformation during the joining process - in terms of the joint strength. The difficulty in designing SPR joints with appropriate strength consists not only in the proper selection of the shape of the rivet and the die profile, but also matching material properties of the rivet and joining sheets.

3. NUMERICAL MODELING

Initially proposed concept of the two forming processes of M-rivet was verified by numerical modeling. As a result a preliminary information about probable stress distribution in the cross section of the M-rivet was obtained, which was another element that allowed comparison of the results of computer simulations with subsequent experiments conducted in the laboratory scale. General assumptions concerning numerical models for M-rivet forming analysis were limited to use simplifications: static, isothermal and axisymmetric

(2D). An elastic - plastic material model with isotropic strain hardening for both sheets and rivet was applied. Tools - die insert and counter-punch - were modeled as an elastic areas. In preliminary analysis verifying the proposed concept of the process, punch was rigid. Additional part - counter-punch pusher - was modeled in all cases as rigid. Finite element mesh consisted of four-node elements. Since the automatic remeshing procedure was needed because of strain gradient existing in joining sheets, especially for top layer, numerical model was initially optimized in terms of remeshing criteria and corresponding parameters [9,10]. In **Figure 4** selected steps of process I modeling are presented, taking into account the equivalent stress distribution in both tools and formed material.

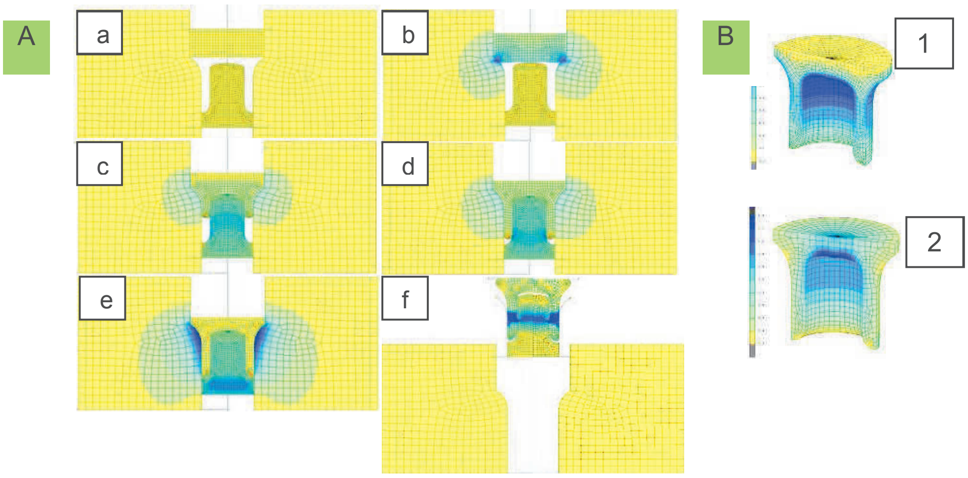


Figure 4 A - Selected simulation steps of the M-rivet forming; "Process I" (material: aluminum 1070, equivalent stress distribution): a) micro-preform positioning, b-e) forward micro-extrusion, f) ejection of the micro-component; B - Example of strain distributions in the M-rivets cross-section: process I (1) and process II (2); material: aluminum alloyal1070

The simulations were performed for a selected materials - aluminum and copper - used for preforms. Visible differences in the distributions of the M-rivet properties were obtained, as shown in **Figure 5b**. The simulation results also indicated that in the process II relatively higher pressure is generated on the counter-punch forehead than in the process I. The analysis of simulation results also revealed that the production of the M-rivet according to the process II using materials with higher yield stress (eg. steel, brass,…) may be very difficult or even impossible to complete. As for cognitive reasons and a verification of the FEM results, process I was chosen first, for different material of relatively low yield stress (following that: relatively simple tools), and then process II.

4. EXPERIMENTAL TRIALS

Analytically determined and obtained from numerical analysis results for tools loading were used to develop the dies design modifications in relation to the pre-proposed, the one-piece version. Two types of dies: die divided transversely - **Figure 5a**, and reinforced die - **Figure 5b**, and punches and counter-punches - **Figures 5d-e**, were designed and manufactured.

Designed tools and the process of micro-riveting were tested on designed, established, prototype stand. Processes proceeded smoothly and tools have functioned properly in terms of strength. Developed concept of the complete experimental stack-up requires the special macro-system with the micro-tool (M-tool) giving the opportunity to exchange easily M-tool components for specific tasks. The whole system is placed on a table of the precise testing machine.

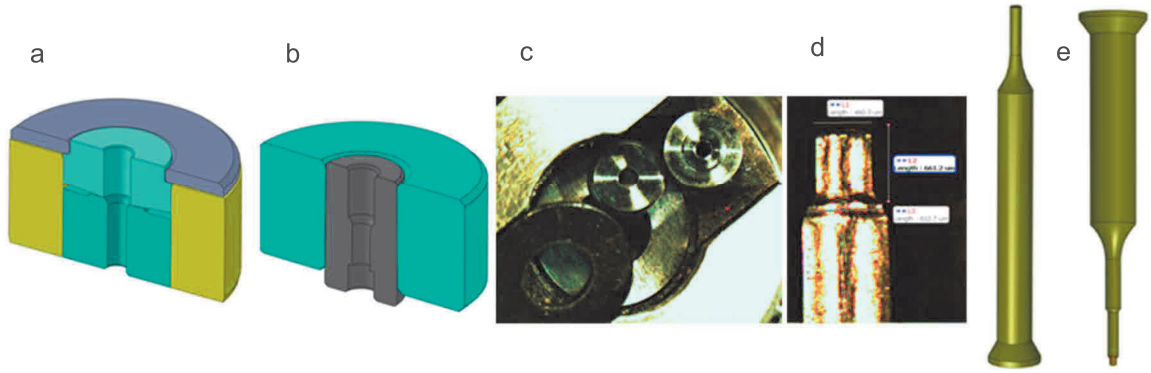


Figure 5 The transversely divided die design (a), reinforced die design (b), transversely divided die on the micro-tool table (c), final shape of the counter-punch (d), the punch (flat forehead) and the counter-punch design (e)

After the system for signal recording was tested, a series of processes of micro-punching of aluminum and copper components with simultaneous registration of force and displacement were carried out. The punch of 1 mm diameter with a clearance of 0.01 mm were applied. Obtained components after micro-punching were used afterwards as preforms for the M-rivets extrusion. **Figure 6** shows comparison of examples of results of FEM modeling and micro-punching experiments.

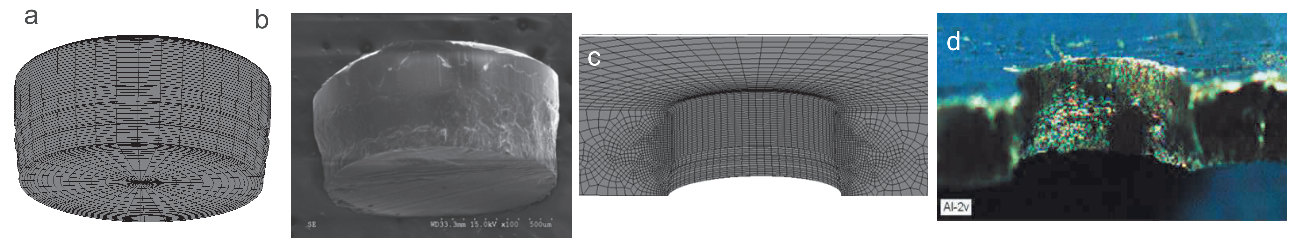


Figure 6 FEM modeling (a) and scanning electronic microscope (b) component shapes after micro-punching and surfaces of the preforms after punching: FEM (c) and experiment (d).

The next step was to carry out tests of micro-extrusion of M-rivets with simultaneous data acquisition of force and displacement, in order to verify the assumptions of designed processes and numerical analysis results. Preforms of 0.5 mm and 1 mm thickness were used for micro-extrusion. Examples of the M-rivets and the corresponding preforms obtained after micro-punching are presented in **Figure 7**, while the **Figure 8** shows examples of metallographic M-rivet specimen. Detailed analysis of the resulting shapes allowed, i.a., for modifications of numerical models of micro-riveting, according to M-rivet shape imperfections, for further, more detailed modelling of micro-riveting.

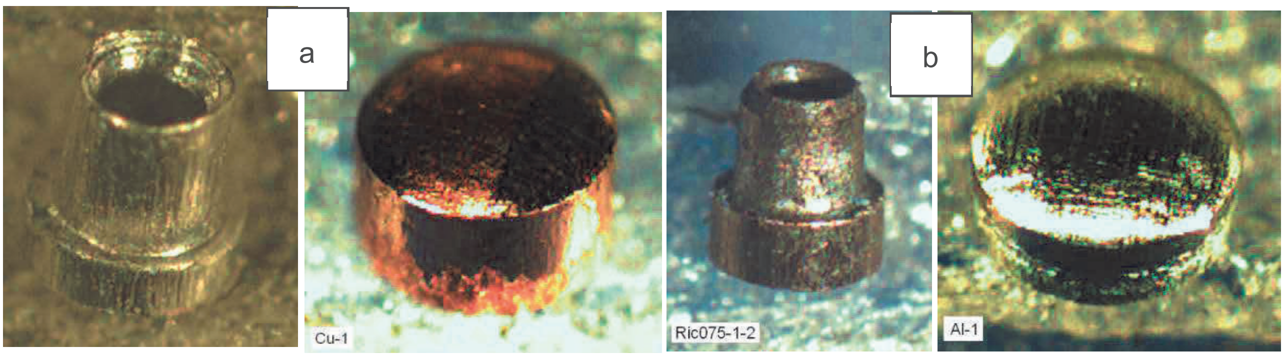
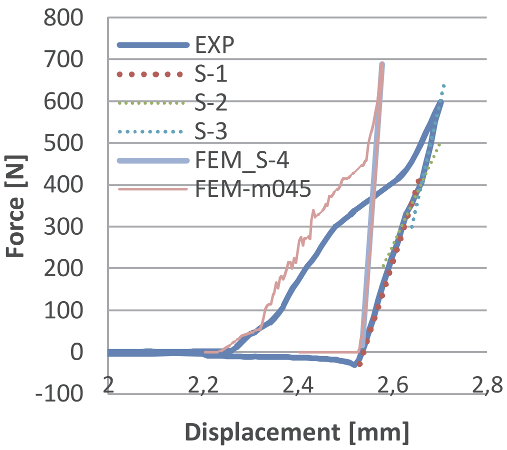
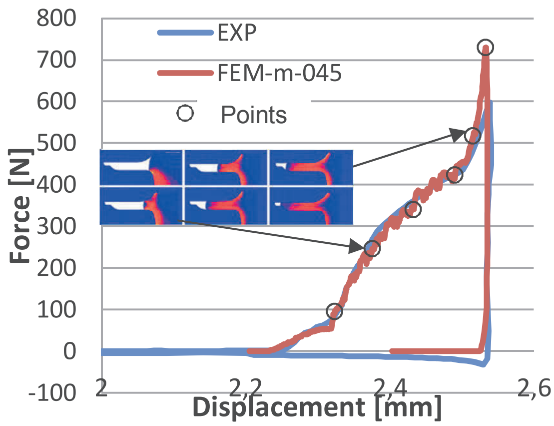


Figure 7 Experimentally obtained preforms and M-rivets: a) copper, b) aluminum



a)



b)

Figure 8 Comparison of the FEM and experimental results: a) determining the stiffness of the loading system for simulation and experiment, b) compensated by elastic deflection waveforms FEM and experiment forces - circles indicate points corresponding to the phases of the simulation

Since the force-displacement history is one of the best ways to verify numerical model with corresponded experimental set-up, stiffness of the experimental stack-up influencing the shape of recorded parameters had to be veryfied. **Figure 8a** shows the method for determining the stiffness in the case of the experimental results and the simulation results. It involves finding compartments linear curve relief. Referred stiffness serve for compensation of the influence of elastic strains on the registered process force. In case of the experiment, compensation took into account three ranges of rigidity and in case of an FEM simulation - one. **Figure 8b** presents the process force flow after described compensation with marked points (circles), which correspond to the phases of the simulation process. Thus the numerical model was verified and can be used for further M-SPR development.

5. CONCLUSIONS

The development of micro-joining: micro-self-piercing riveting (M-SPR) and micro-clinching (M-C), require designing special tooling and, in case of the M-SPR, the development of production technology of micro-rivets (M-rivets). Initial assumption is to make joints with dimensions less than 1mm. The process of micro-rivet (M-rivet) forming for micro-self-piercing riveting (M-SPR) has been proposed in two versions, and verified by numerical analysis with an experimental verification. Experimental trials have confirmed most of the assumptions based on numerical analysis concerning both: M-tools behavior and M-rivet forming process. Further work will be concentrated on micro-joining development. An attempt to develop technology for micro-rivet production and an assessment of their applicability to join micro-elements is an original contribution to research in the field of micro-joining and micro-forming.

REFERENCES

[1] BOKHARI, N., LAPENSEE, M. Self-Piercing Riveting in Automotive Applications, *Mechanical Fastening Seminar*, Jan. 27th, 1998, Troy, Michigan.

[2] LI, B., FATEMI, A. An experimental investigation of deformation and fatigue behaviour of coach peel riveted joints. *International Journal of Fatigue*, 2006, vol.28, pp. 9-18.

[3] CACKO, R. Review of different material separation criteria in numerical modeling of the self-piercing riveting process - SPR, *Archives of Civil and Mechanical Engineering*, 2008, vol. 8, no. 2, pp.21-30.

[4] SUN, X., KHALEEL, M.A. Strength estimation of self-piercing rivets using lower bound limit load analysis. *Science and Technology of Welding and Joining*, 2005, vol. 10, no. 5, pp. 624- 535.

[5] MASUZAWA, T. State of the art of the micromachining. *Annals of the CIRP*, 2002, vol.49, no.2, 2000, pp. 473-488.

[6] GEIGER, M., MESSNER, A., ENGEL, U. Production of microparts - size effects in bulk metal forming, similarity theory. *Production engineering*, 1997, no. 4, pp. 55-58.

[7] GEIGER, M., MESSNER, A., ENGEL, U., KALS, R., VOLLERSTEN, F. Design of micro-forming processes - fundamentals, material data and friction behavior, *Proc. of the 9th international cold forging congress*, 1995, pp. 155-164.

[8] CACKO, R., PRESZ, W. Analysis of the influence of a rivet yield stress distribution on the micro-SPR joint - initial approach, *Archives of Civil and Mechanical Engineering*, 2010, vol. 10, no. 4, pp.69-75.

[9] PRESZ, W., CACKO, R. Influence of Micro-Rivet Manufacturing Process on Quality of Micro-Joint", *14th International Conference on Material Forming ESAFORM*, 2011, pp. 541-546.

[10] MESSNER, A., ENEGEl, U., GEIGER, M. Numerical simulation of metal forming for the production of microparts. *Proceedings of the 30th plenary meeting of the international cold forging group ICTP*, 1997, pp. 1-6.