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ANALYSIS OF STRESS DISTRIBUTION IN THE DIE DURING THE SELF-PIERCING RIVETING PROCESS

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S u m m a r y

In the paper an analysis of the result obtained in numerical simulation of tools load during Al Mg 4.5Mn0.7 aluminium alloy sheets joining by SPR process. Numerical simulations of joining process were made, with use finite element method (FEM), in MSC.Marc 2010 commercial program. Experimental research of SPR joining process was made on test stand: press with electric drive and special tools. High precision of joint cross-sections from experimental and numerical research was obtained. It was observed that the surface pressure on the punch face depend on the rivet deformation and they are changing it non-linear way. The stress distribution change along line on the rivet head surface, through its center, is determined by the recess size of the tubular part of the rivet in the joined sheets. The results of numerical simulation can be used in developing process of SPR tools with shape modification.

Keywords: FEM, self-piercing riveting, tools load, tools for plastic forming

Analiza rozkładu naprężeń w matrycy w procesie nitowania bezotoworowego

S t r e s z c z e n i e

W pracy przedstawiono analizę wyników symulacji numerycznej obciążenia narzędzi w trakcie procesu SPR łączenia blach ze stopu aluminium Al Mg 4.5Mn0.7. Symulację numeryczną kształtowania połączenia wykonano metodą elementów skończonych (MES) z zastosowaniem komercyjnego programu MSC.Marc 2010. Próbę eksperymentalną połączenia zrealizowano na stanowisku badawczym składającym się z prasy o napędzie elektrycznym i zestawu narzędzi. Stwierdzono dużą dokładność kształtowania połączenia uzyskaną w eksperymencie i w symulacji numerycznej MES. Wykazano, że nacisk powierzchniowy na czole stempla formującego zależy od odkształcenia nita – nie zmienia się w sposób liniowy. Zmiana rozkładu naprężeń na przekroju głowy nita jest uwarunkowana głębokością zagłębienia części rurkowej łącznika w warstwę blach. Uzyskane wyniki symulacji numerycznej mogą stanowić podstawę do opracowania zmodyfikowanego kształtu narzędzi do kształtowania połączenia SPR.

Słowa kluczowe: symulacja numeryczna MES, nitowanie bezotworowe, obciążenie narzędzi, narzędzia do plastycznego formowania

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1. Introduction

Forming process of self-piercing rivet joints (“SPR”), is a usually cold process with large plastic deformation [1-4]. Most often it is used for joining materials with good ductility. It belongs to a group of joining technologies strongly developed in automotive industry [5]. Modern cars, for example BMW 5 Series and Audi A2, in its design already have hundreds of SPR steel rivets (Fig. 1). Not only this companies sued SPR joints. Another company, which was one of the first to use SPR joining technology, is Jaguar Land Rover.

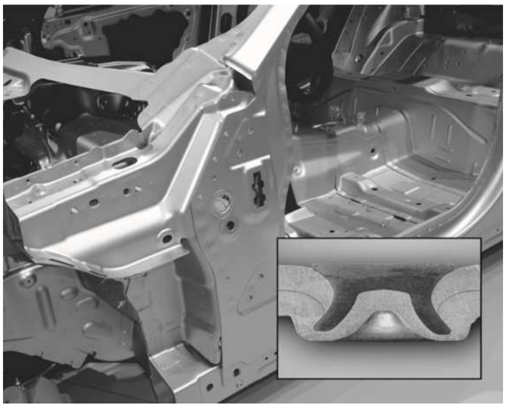

Fig. 1. Motorcar body structure with SPR joints

One of the research direction is the use of SPR joining technology to joining sheets made of titanium alloy [6, 7]. In the case of hard, low plasticity materials the SPR joining process can be performed with sheet laser heating („LSPR” – laser asisted self-piercing riveting) [8, 9]. Hardly deformable material is heated up before joining. Another way of joining, with a local temperature increase, is a process with additional rivet rotary movement („FSPR” – friction self-piercing riveting) [10]. Completely different variety of self-piercing riveting joining technology, for joining sheets with different plasticity, is the use of the solid rivet in joining process („SSPR” – solid self-piercing riveting) [11, 12].

In forming process of SPR joints a large pressing force is required. Hence, the forming tools (punch and die) are also loaded by pressing force. Punch geometry and mechanical properties of joined sheets affect on the loading force – punch displacement characteristic. The intensity of the material strengthening during the process results in changing of tool load, that in case of surface pressure achieve value above 1000-1500 MPa [13]. Even most modern methodology of experimental research does not allow to do analysis of the stress distribution in forming tools. The influence of joining process parameters on the interlock size can obtained in numerical analysis (FEM) [14-16].

Tools for plastic forming often work at high loads [17, 18]. In some cases, the pressure may exceed the steel tool strength [19-22]. Thus, knowledge of the value and distribution of the stress will allow to determine the tools area, which are most sensitive on the changing of the SPR joining parameters.

2. Research procedures

Due to the large number of die shapes only one case of riveting process with a specific tools (punch, die and blank holder) was taken into account. During geometry modeling process of the rivet and die the parameters of these tools were taken from Böllhoff company. The finite element method (MSC Marc Mentat) was used to loads modeling and stress distribution determining [23, 24].

2.1. Experimental research

In experimental and numerical simulation of joint forming process EN-AW Al Mg 4.5Mn0.7 aluminium alloy sheets were used. Chemical composition of the sheet is presented in Table 1. For the rivet and sheets yield strength and work-hardening curve parameters were determined (Table 2). In the analysis the sheets thickness were: top sheet $t_1 = 0.5$ mm and bottom sheet $t_2 = 1.5$ mm. The rivet was made of low-carbon steel with properties developed by Henrob company (C50542AZ04 rivet) and the hardness was 460HV.

Table 1. Chemical composition of Al Mg 4.5Mn0.7

Composition, % mas.									
Mg	Mn	Cr	Si	Fe	Cu	Zn	Ti	Other elements	
4.5	0.6	0.2	0.3	0.2	0.1	0.25	0.15	0.05 (single)	0.15 (together)

Table 2. Material and mechanical properties of rivet and sheets

Material		**Mechanical properties**		
		Young's modulus E, MPa	**Yield stress $\sigma_{0.2}$, MPa**	**Work-hardening curve**
Rivet	Boron steel	188000	1520	$\sigma_p = 1659\varepsilon_p^{0.014}$
Sheets	Aluminium alloy	75000	135	$\sigma_p = 505\varepsilon_p^{0.191}$

SPR joint forming was realized on the Tox Pressotechnik press with maximum force load 100 kN and with use of Henrob company tool head. General structure of the tool head was shown in Fig. 2, and die and rivet were presented in Fig. 3.

a) b) c)

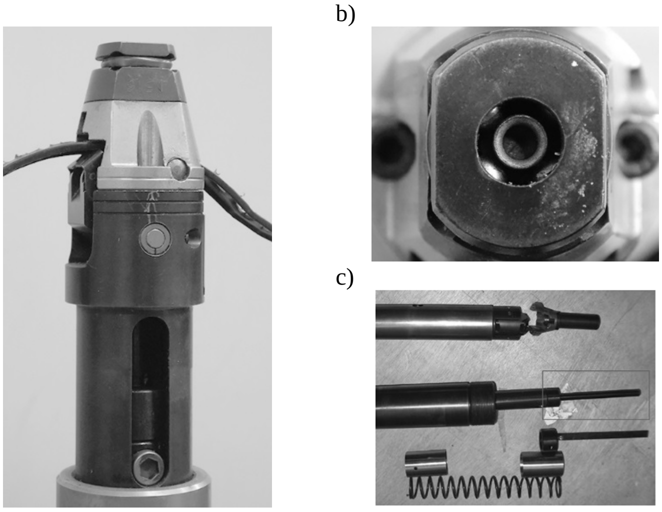

Fig. 2. SPR tool housing: a) punch head, b) blank holder face, c) tool head elements (punch highlighted in the box)

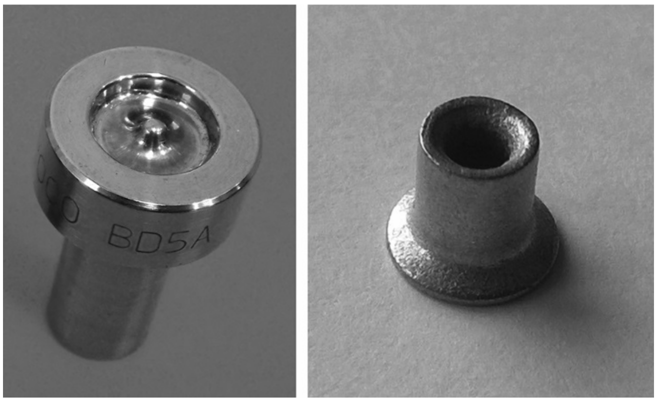

Fig. 3. Views of die (left) and rivet (right) used in SPR joining process

2.2. Numerical research

For the numerical calculation the sheets and rivet were modeled using elastic-plastic material model with isotropic work-hardening using type 10 quadrilateral axisymmetric elements. While for the other solids, i.e. punch, blank holder and die a 1.2714 tool steel (according the ISO-B standard) was assigned.

Due to large number of SPR joining technologies and its parameters (combinations tool) in the study only one case of self-piercing riveting joint forming was analyzed for a specific set of tool: die, punch, blank holder and for a specific sheets thickness arrangement. Tools loads were modeled in MSC Marc Mentat software. Die and rivet parameters, during the geometry modeling, were taken from the Böllhoff tool information.

The top sheet was divided into 300 elements and the bottom sheet into 180 elements. Rivet was divided into 334 elements (fixed number of elements). For other solids, i.e. punch, blank holder and die a tool steel was assigned. In all contact surfaces Coulomb friction model was adopted with μ = 0.1 friction coefficient.

Due to a form of the joint itself and the course of forming, the self-piercing riveting process may be considered using the two-dimensional axisymmetric model - the axisymmetric state of stress and strains. A 2D axisymmetric model of the riveting process was generated including two sheets to be joined, the rivet and the tools. The boundary conditions have been defined based on the SPR riveting (Fig. 4). When modeling the basic die and rivet form, the corresponding geometry parameters of Böllhoff tooling have been used. During the numerical simulation, for certain relative rivet movements, the pressure distribution along the OA and OB lines and stress distribution in longitudinal section of the die were read (Fig. 4).

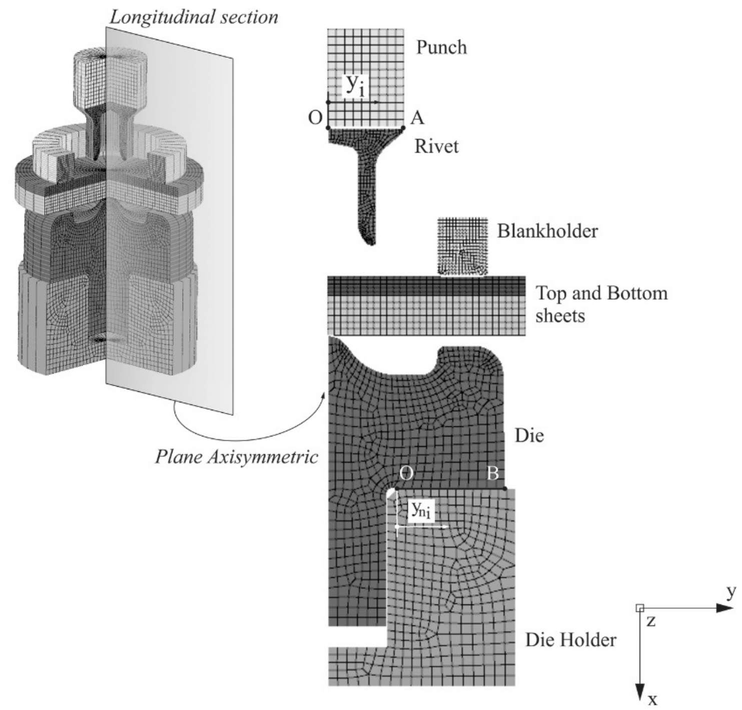

Fig. 4. View of the numerical model of riveted joint elements before riveting and tools with specified boundary conditions and lines to check of stress

In order to carry out correct and stable numerical calculations, advanced grid regeneration algorithms were used. The joined sheet plates are subject to huge local plastic strains when the SPR joint is being created. The mesh rendering algorithm was used in order to achieve correct and stable numerical calculations. The maximum allowed element length of 0.2 mm was taken as a parameter.

3. Results and discussion

Tools stress distribution results from the load history in the SPR joining process. The step of sheets clamping to the die surface and the rivet pressing step provide an information about load history of tool head individual elements [25]. Thus, the self-piercing riveting joining process can be characterized by specify three main steps: sheets clamping, rivet pressing, tools retract [26]. Therefore, during the joining process in the first step of riveting the sheets clamping, to the die surface by blank holder, is realized (Fig. 5a). As the result the initial sheet deformation is obtained. Then the rivet is progressively pressed into sheets (Fig. 5b). Stress distribution after sheets clamping to the die surface was presented in Fig. 6.

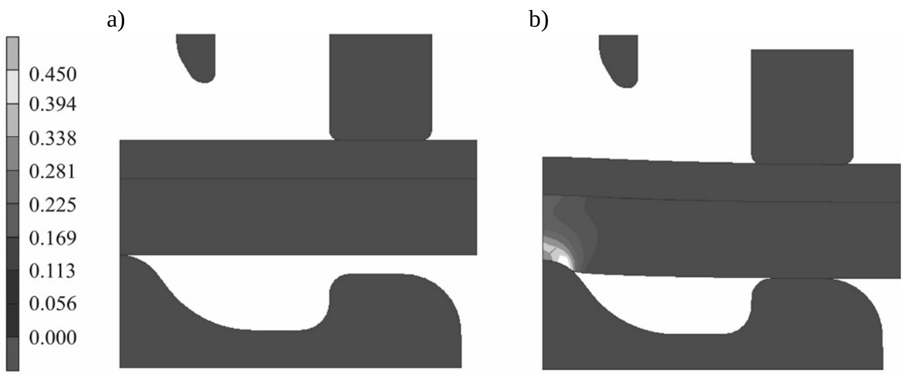

Fig. 5. Intensity distribution of plastic deformation during initial step of joint forming: a) sheets arrangement before joining, b) end of the clamping step

From the moment of contact between rivet inner surface and top sheet surface (area in Fig. 7), the joining process is continued with greater extension, in the radial direction, of tubular part of rivet. At the end of rivet pressing step a slight “rivet sizing” into die cavity is observed, so as to obtain a “closed” and tight joint. After punch retract a joint spring-back effect is observed, which causes an insignificant movement of rivet. Because of rivet locked into sheet material, the free surface of rivet head is pushed outwards (in the x axis direction – Fig. 8). The size of spring-back effect along the line on the rivet surface was presented in Fig. 8 as a dashed line.

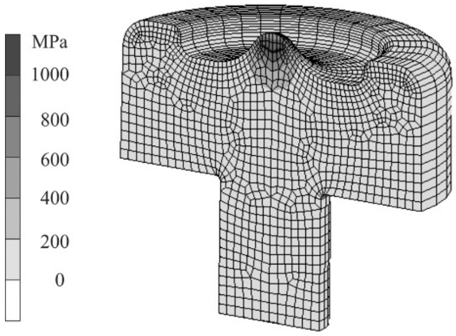

Fig. 6. H-M-H reduced stress distribution
in the die after sheets clamping

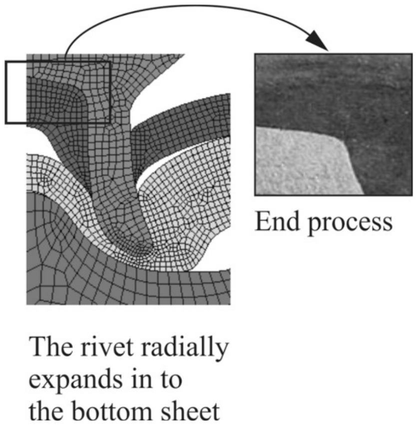

Fig. 7. Contact of the rivet head with top sheet
in the self- piercing riveting process

During the SPR joint forming process the rivet is gradually pressed into sheets. As a results the rivet is greatly deformed, on the contact surface between rivet and punch the surface pressure occurs due to the punch load. Despite the fact that the punch has got a high rigidity on its face the deformations were observed (solid line in Fig. 8). Deformation distribution depends on the rivet shape (the stiffness depends on the shape) [16]. Rivet in the central part has got an hole which allows for specific deformation of the tubular tart of rivet. Rivet areas are deformed with varying degrees, which affects the pressure distribution on the punch face. The stress distribution on the rivet head surface is not uniform, and it is not constant during the joining process. Stress values at particular points on the rivet head (along the line through the rivet vertical axis) are different and they are changing during the joining process in dependence of the rivet deformation. With increasing the rivet pressing into sheet material (also movement of the punch face

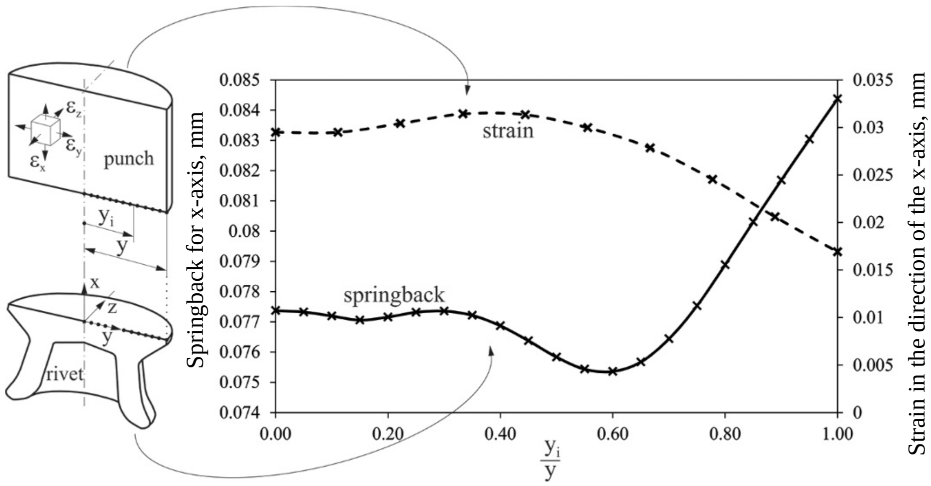

Fig. 8. Axial deformation on the punch surface and the size of spring-back effect of the rivet head along OA line (indicated in Fig. 4)

surface) the pressure on the punch face increase – Fig. 9. During the numerical analysis of the tool load, the maximum pressure value is not located on the rivet head axis but in the area of tubular part of rivet. In this case, it is the pressure level on the rivet and punch surface at the end of rivet pressing step, before punch retract. This is due to the increase of rivet deformation and its strengthening in specific areas. In the rivet axis the stress level is lowered, and this is due to the fact that a rivet got a hole from the bottom (tubular part of rivet) and there is no full load transferring. Classically in contact of cylinder face with full body the maximum pressure is in axis on the face.

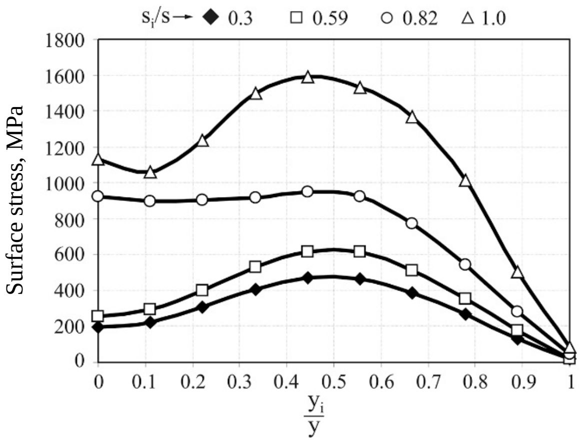

Fig. 9. Pressure distribution depending on the punch relative displacement (s_i/s) for each values of relative distance from the punch axis (y_{ni}/y_n)

To do an analysis of the die load it must be taken into account the stress distribution from the blank holder and from the joint forming process. The level and variety of the pressure from the blank holder is relatively small compared to the pressure form the joint forming. The stress distribution along the line of contact between die and tool head housing (OB line – Fig. 4) for relative punch displacement was presented in Fig. 10. With increase of rivet recess into sheet material the forming resistance increase and consequently the die load also increase. The stress on the die – tool head housing contact surface increases, and the area of their occurrence also increases. The die from the beginning of rivet pressing step is loaded in the conical part, which is not insignificant in terms of the die shape elastic deformation at the die mount.

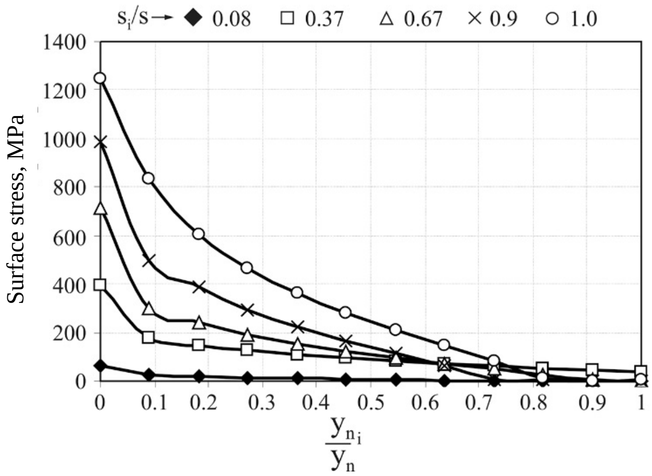

Fig. 10. Pressure distribution depending on the punch relative displacement (s_i/s) for each values of relative distance from the tool head housing hole (y_{ni}/y_n)

Due to the fact that the profile of the die cavity is not a straight line, to illustrate the stress distribution in material a 3D model was created (by using procedures of result transformation from the axisymmetric 2D model to the 3D model). The clamping step of sheets to the die surface is related to their simultaneous bending and pressing into die, and this leads to pre-load of the die (Fig. 6). Further privet pressing results in increase of stress level and its distribution (Fig. 11a-d). At the end of rivet pressing step, for the maximum punch displacement, the stress level was the highest. The die dangerous area was located near the edge fillet (Fig. 11d) – the transition from the die bearing surface to the hold-fixing surface.

Verification of model assumptions and results of numerical simulation was made based on the joint cross-section from the experiment. Maximum forming force wal also compared. Standard deviation was less than 5%. The cross-section shape between FE analysis and the experiment is compared in Fig. 12. The cross-section of the self-piercing riveting joint has a similar shape and deformation mode as with the FE analysis result.

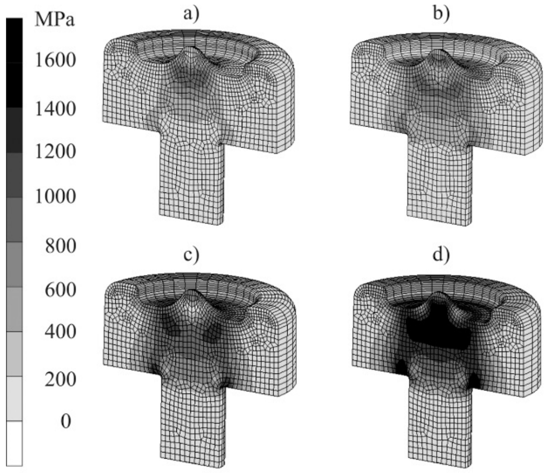

Fig. 11. Distribution of reduced stress according to HMH theory
for displacement of rivet s_i/s [mm]: a) 0.3, b) 0.59, c) 0.82, d) 1.0.

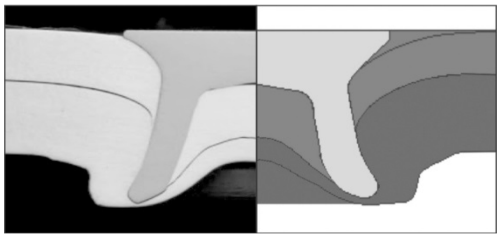

Fig. 12. Joint cross-section from experiment (left side)
and from FEM simulation (right side)

4. Conclusions

SPR joint forming process is a complex issue, it is a strongly non-linear process because of: non-linear analysis, boundary conditions at the contact surfaces, sheets and rivet non-linear material models and complex tools geometry. Therefore, there is a different stress level for each of forming tools (punch, die or blank holder). The stress level in specific areas are not constant, and it is changing in dependence of rivet into sheet material recess size (the punch movement). Hence, there is a need to observe the stress level in the material over the joining process time, which is possible by numerical calculations.

The most dangerous moment for the forming tools is the rivet sizing phase. The observed H-M-H reduced stress levels and tools pressure are larger than average during the whole joining process. The force load is transmitted by the die material.

As a results of computer modeling of joining process were: the stress distribution, pressures and deformations of forming tools. The information obtained in numerical simulations (pressure on the die surface and the deformed material displacement velocity) allow for further analysis to determine the die cavity areas in which the pressure and the path of friction are the greatest. This will allow to make a die shape optimization with taking into account the die durability and quality indicators of the SPR joint.

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