DEVELOPMENT OF THE TECHNOLOGY FOR FORMATION OF MECHANICAL AND GLUED-MECHANICAL JOINTS BY THE PUNCHING METHOD*

Yu.S. VASILIEV, L.S. PARSHUTINA and **A.N. CHUKASHKIN**
E.O. Paton Electric Welding Institute, NASU, Kiev, Ukraine

The processes of formation of mechanical joints in thin-sheet materials with anticorrosive coatings by the punching method using glue compositions of different viscosities between the mating surfaces were investigated. The limiting values of rheological characteristics of the glues that affect formation of the glued-mechanical joints were established. The cold-cured highly filled glue composition on a silicon-polyurethane base, not preventing formation of the glued-mechanical joints, was developed. Press equipment based on a pneumatic actuator, providing a compression force of up to 20 kN, was developed and manufactured.

Keywords: *mechanical joints, glued-mechanical joints, thin-sheet metal structures, forming technologies, hybrid glue compositions, filling compounds, polydisperse filling*

Competition between materials in transport machine building is determined by continuously growing requirements for reduction of weight of structures, improvement of reliability, extension of service life of vehicles, and ensuring comfort and environmental friendliness. The share of aluminium alloys, plastics and composite materials used to produce vehicle bodies constantly increases. Nevertheless, steel continues to be a promising material. It will dominate in transport machine building in the future because of its technological innovation potential, high affordability and environmental friendliness [1]. When using increased- and high-strength steels, reduction of sheet thickness allows maintaining cost characteristics of a vehicle, but leads to a substantial increase in requirements for reliable and durable corrosion protection of a structure.

It is a known fact that galvanising is the most effective method for anticorrosive treatment of thin-sheet steels used to produce vehicle bodies, which is attributable to its peculiar electrochemical mechanism of metal protection. Combined systems containing metallised and polymeric coatings, which are characterised by high deformability, weldability and ageing resistance gain an increasingly wider popularity. Development and application of new materials and coatings require mastering of the advanced methods for joining components of vehicle structures.

Application of the glued joints in components of thin-sheet structures, which do not experience high loads, has been widening lately in a number of industries. The reason is that the glued joints have low reliability characteristics in non-uniform pulling and tear. Moreover, the glued joints have drawbacks related to variations in properties of the glues as a result of ageing, necessity of forming contact pressure and fixation of parts in curing of the glues. Therefore, the trend is to combine the glued joints with joints produced by other methods, providing additional local bonds between the parts.

The combined glued-welded joints made by resistance spot welding (RSW) of parts over the layer of the glue preliminarily deposited on the mating surfaces are widely applied in production of thin-sheet structures from low-alloy steels [2]. However, RSW of coated metal sheets involves some difficulties. Moreover, the high-temperature effect of RSW causes burn-out of metallic and organic coatings, this requiring the use of additional operations for corrosion protection.

The glued-riveted and glued-bolted joints are characterised by the highest strength properties, particularly under dynamic loading conditions. However, the presence of holes in the parts joined does not only lead to weakening of a section, but also create some technological difficulties in the process of formation of permanent joints.

Application of the local deformation technology by pressing the metal sheets to be joined into the die with a punch eliminates many problems in formation of the combined joints [3]. Many design and technology solutions to provide formation of the «dovetail» type joints (Figure 1) were patented. It should be noted that, as a rule, the information available on such joining methods is incomplete. Only the flow-charts of the processes used to manufacture the joints can be found, without disclosure of principles of design

*The article was prepared on the basis of results of accomplishment of the NASU targeted integrated program «Problems of Remaining Life and Safe Operation of Structures, Constructions and Machines» (2007–2009).

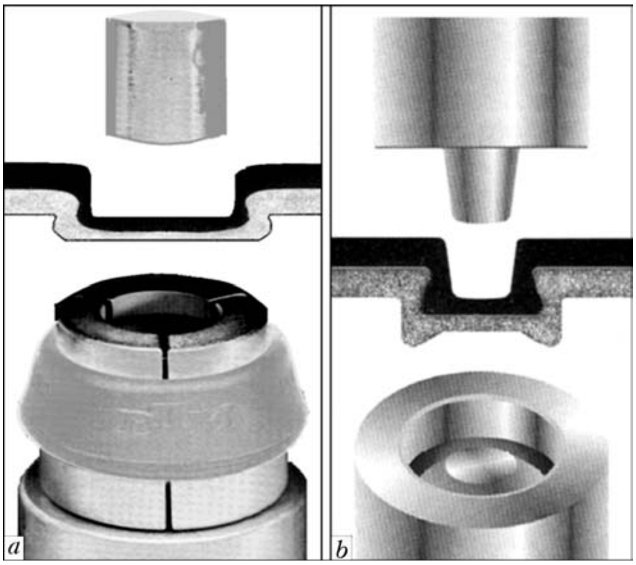

Figure 1. Joints produced by the punching method: *a* — clinch; *b* — TOX

of the equipment and calculation of parameters of forced formation of the joints.

The purpose of this study was to develop recommendations on the technology for formation of mechanical and glued-mechanical joints on galvanised steels by the punching method in order to extend life of thin-sheet structures applied in transport machine building. The problems solved were as follows:

• processes of contact interaction in punching of the metal sheets joined into the die were investigated;

• requirements to rheological and physical-mechanical characteristics of the glues to produce sound joints were identified;

• and technology and experimental equipment were developed for formation of the mechanical and glued-mechanical joints on galvanised metal sheets.

Formation of the joints by the punching method belongs to the category of technologies for pressure treatment of metals and consists of a number of successive operations: fixation of the metal sheets with a clamping element (Figure 2, *a*), punching of the sheets joined until they contact the anvil (drawing) (Figure 2, *b*), upsetting of the sheets with decrease in their thickness and simultaneous increase in their cross-section area (Figure 2, *c*), and removal of a finished joint (Figure 2, *d*) [4, 5].

Analysis of the stress-strain state during the drawing process shows that plastic deformation is mainly concentrated only within the overlap portion of the sheets, which is located on a flat face of the die and its rounded edge. Increase in the radius of rounding of the die, r_d, causes decrease in localisation of plastic deformation in the bent section. Deformation of the sheets on the punch face is characterised by the fact that metal gradually bends over the rounded edge of the punch at the initial moment of drawing, when the load has not yet reached its maximal value. If the radius of rounding of the punch edge is small compared to its diameter, the bend with plastic deformation will not coincide in time with the peak load, and will have no significant effect on the latter.

Investigations of the process of formation of the joints by punching were carried out by using 0.55 and 1 mm thick sheets of cold-rolled low-carbon steel 08kp (rimmed) galvanised by the electrolytic method on both sides. This steel belongs to the materials of deep drawing, and is widely used in formed-welded structures applied in transport machine building.

Rigid TOX-die and opening clinch-die were developed, allowing formation of the joints on metal sheets of different thicknesses due to varying internal diameter and height of a forming bushing (Figure 3, *a, b*). Technological investigations were conducted by loading the punch–die system in a clip (Figure 3, *c*) using testing machine ZD-10, and by recording the compression force depending upon the punch movement.

As established, for the clinch- and TOX-dies it is indicated to use gap z of a different width between the punch and die wall. With a smaller gap than total thickness of the sheets joined ($z < t_0$), thinning of the «sleeve» wall to a preset value occurs at a small decrease in thickness of the metal sheet at the punch face. This approach was used to design the rigid TOX-die. To reduce stresses, the radius of rounding of the leading edge of the die was increased to $r_d \sim (0.25–0.40)t_0$.

In the technology of formation of clinch-joints the drawing stage should be performed without wall thinning at gap $z > 1.1t_0$, as opening of the clinch-die during formation is undesirable. At a minimal value of the radius of rounding of the die, $r_d \sim (0.05–0.10)t_0$, stresses in the dangerous section substantially grow.

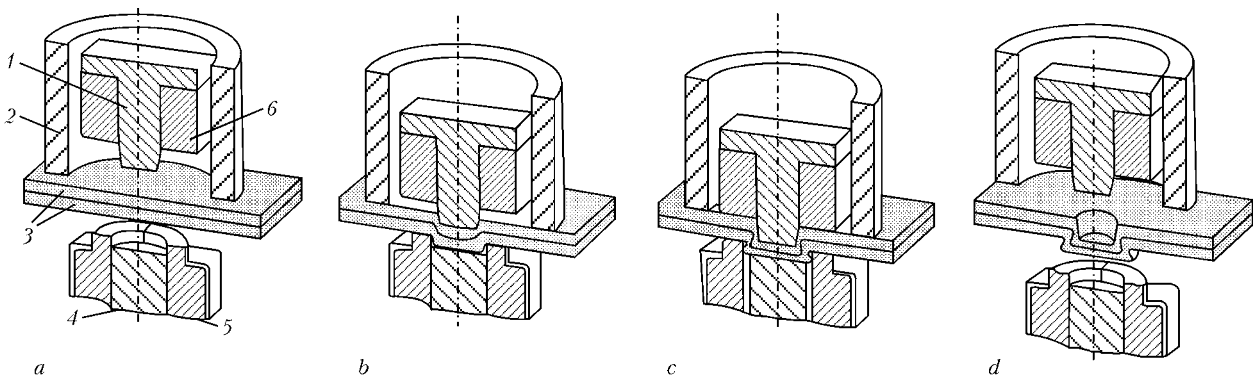

Figure 2. Flowchart of formation joints by punching using an opening die (clinch-joint) [5]: *a–d* — see in the text; *1* — punch; *2* — clamp; *3* — sheets joined; *4* — anvil; *5* — opening die; *6* — limiter

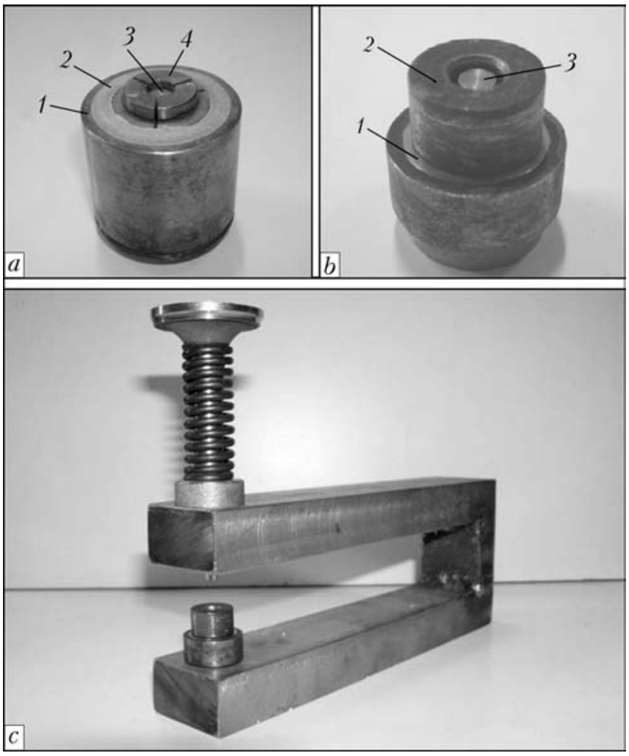

Figure 3. Devices for formation of joints by the punching method: *a* — opening clinch-die (*1* — forming head of the collet type; *2* — anvil; *3* — elastic bushing; *4* — conductor); *b* — mountable-and-dismountable TOX-die (*1* — forming bushing; *2* — adjustment gasket; *3* — anvil); *c* — appearance of clip

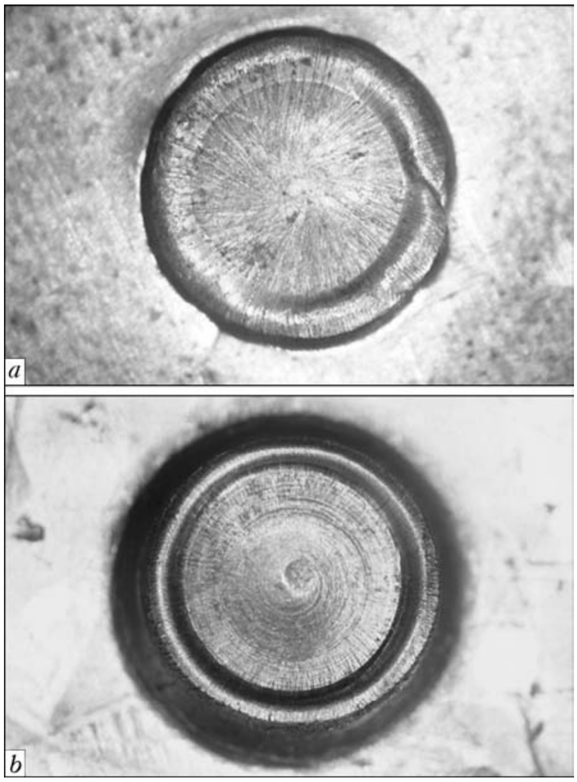

Figure 4. Mechanical lock on the die side in clinch- (*a*) and TOX-joints (*b*)

However, in deep drawing to $1.5t_0$, although tensile bend stresses exceed the values of yield stress of the metal, but displacement of a sheet over the die face prevents opening of the die.

Formation of the «dovetail» takes place in the process of upsetting of the sheets joined between the punch and die anvil. Drawing of the working surfaces together leads to metal flow from centre to periphery, and deformation occurs in a stepwise manner to form riffles at the steel 08kp–zinc coating–die anvil interface. This is accompanied by formation of the so-called collars, where continuity of the zinc coating may be broken (Figure 4, *a*).

Formation of the TOX-joint takes place as a result of the metal flow between the die anvil and punch into the closed volume of cavity on the anvil perimeter. This process corresponds to cold forming with forced drawing of metal. Formation of a «button» joint occurs at a tighter interaction of the metal sheets subjected to orientation thinning. Formation of the joint in a closed volume limits surface deformation of a metal sheet, thus maintaining continuity of the zinc coating (Figure 4, *b*).

It is reported [6] that the use of glue compositions with viscosity of up to 50 Pa·s has no substantial effect on the process of formation of the glued-mechanical joints made by the punching method. However, it makes the entire technological cycle more complicated. There is a problem of dosed deposition of liquid glues on the mating surfaces, while pressing out from the overlap cavity leads to contamination of a workpiece, equipment and process fixture. Viscosity of a glue composition is adjusted by adding various filling agents. While reinforcing the glue interlayer, these agents retain the glue in the overlap gap, help to maintain uniform thickness of the glue layer after deposition of the glue on the curvilinear surfaces, and increase strength characteristics and crack resistance of the glue interlayer.

Investigations of the effect of the glue interlayer on the process of formation of the clinch- and TOX-joints were carried out by using epoxy-polyurethane glue composition EPU with different filling degrees: EPU-K with effective viscosity of about 80 Pa·s, EPU-N — about 200 Pa·s, and EPU-P — paste-like.

As established, composition EPU-K can be readily pressed out from the contact area, and it does not prevent formation of sound joints. At the same time, compositions EPU-N and EPU-P exert different effects at all stages of formation of the joints in the clinch- and TOX-dies. Two variants of accumulation of glue EPU-N were observed in the clinch-joint, where formation occurs without thinning of the sheets joined: in the circumferential zone under a clamp, and in the upset plastic flow zone behind the edge of the working surface of the punch (Figure 5, *a*). The last case is characterised by cracking of the «button» that forms recesses, this leading to contamination of the opening die.

The negative effect of glue EPU-P on formation of the TOX-joint was fixed as early as at the stage of pressing the sheets together and applying load to the punch. The zone of uniform compression forms at the «button» centre. It prevents movement of the paste

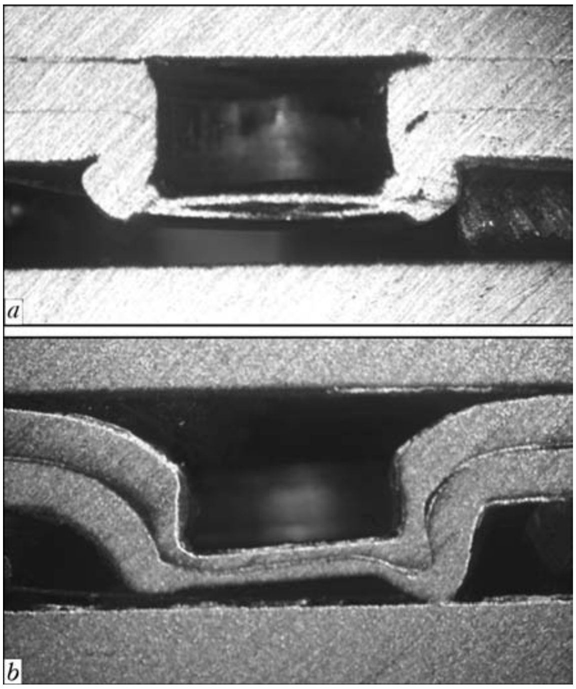

Figure 5. Sections of the glued-mechanical clinch-joint (glue EPU-N) (*a*) and TOX-joint (glue EPU-P) (*b*)

to the circumferential drawing formation zone. The glue appears to be in the closed space and forms a «pocket» that separates the sheets being joined. At the stage of upsetting, the glue is pressed out from the «pocket» to the necking region and hinders formation of the «dovetail» (Figure 5, *b*). The use of glue EPU-N with viscosity of about 200 Pa·s excludes formation of the «pocket» and provides the sound TOX-joint.

In hybrid overlap joints, misalignment of application of load results in their deformation, thus causing redistribution of stresses in the glue layer and their concentration at the overlap end. Upon reaching the level of ultimate stresses, the glue layer fractures and the hybrid joint works as a purely welded or riveted one.

Tensile shear tests of the glued-mechanical specimens showed that strength of the clinch- and TOX-joints with compositions EPU-K and EPU-N is almost identical. Initial fracture occurred in the glue interlayer under the loads twice as high as in the specimens without glue, i.e. the main load is taken up by the glue interlayer, while the rivet functions as a retainer in polymerisation of the glue.

Operation of cars with glued-mechanical joints showed that the cured epoxy glue interlayer is sensitive to surface cracking under dynamic loading and thermal cycling. Intergrowth of cracks leads to their filling up with aggressive media and intensification of crevice corrosion.

Capabilities of formulation methods for regulation of service properties of epoxy glue compositions are limited by narrow ranges of variations in the components making up the system (plasticisers, solvents, filling agents, etc.), the content of which is determined by technological requirements for formation of sound glued-mechanical joints. Therefore, the search for new alternative methods to improve rheological and deformation characteristics of the filled glue compositions is still of current importance.

Investigations were carried out to study a hybrid glue composition (HGC) produced by combining raw rubber and polyurethane, which turned out to be promising in terms of a wider variation of deformation-strength and rheological properties. Organic-silicon elastomer served as a rubber component. The presence of chain-terminal functional groups (Si–OH) in its chain plays an important role in the mechanism of «cold» curing, as the rates of reaction of prepolymer of the urethane matrix with chain-terminal isocyanate groups and silicon are comparable. This made it possible to produce a single-component system in the form of a finished glue composition in the sealed container packing. Curing of this material results from interaction of the atmospheric moisture with hydrolytically unstable groups in molecules of a structuring agent and subsequent reaction with blocked chain-terminal groups of silicon and prepolymer.

Investigation of physical-mechanical properties of the experimental HGC showed their high adhesiveness to aluminium alloys and galvanised steel, as well as to oiled surfaces resulting from the forming process (tensile shear fracture of glued specimens was of a cohesion character). At the same time, high (up to 400 %) elongation is characteristic of elastomeric sealants that effectively protect the overlap joint from crevice corrosion. To use HGC as a structural glue, it is necessary to increase the elasticity modulus and mechanical strength, i.e. the degree of its resistance to external force effects.

Decisive role in physical and, first of all, mechanical properties of the cured glue interlayer is played by the frame of hard particles and fibres, i.e. their packing, orientation and degree of filling of the volume. According to the theory of polydisperse filling [7], the highest effect of strengthening of the glue composition structure is provided by discontinuous granulometry of disperse particles. In this case, fine particles fill up the cavities that inevitably form between coarser particles.

It was established that not only arranging of molecules of the hybrid matrix into a kinetically beneficial position, but also redistribution of intermolecular bonds that catalyse polymerisation reactions occur under the effect of the hard surface of an active filling agent. Here the hydrogen bonds play an important role. Therefore, the non-hydrophobised silicas containing OH-groups on their surface accelerate cross-linking reactions, whereas the hydrophobised ones have no effect.

Hard powders of different chemical nature and degree of dispersion (aerosil, kaolin, aluminium powder, ultra-dispersed silicon carbide powder, high-dispersed iron powder and commercial graphite) were used to investigate filling of the experimental polymeric hybrid matrix.

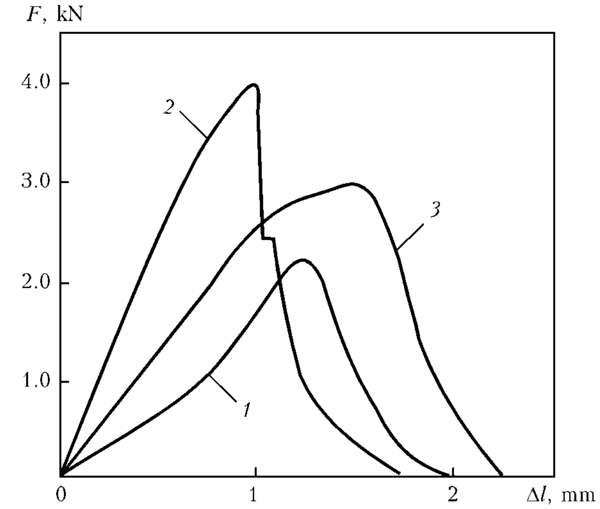

Figure 6. Diagram «force F–deformation Δl» for mechanical (*3*) and glued-mechanical joints with experimental hybrid glued compositions GKK-1 (*1*) and GKK-2 (*2*)

It was found that adding aerosil and kaolin, having on their surface the active groups capable of interacting with the polyurethane component of the hybrid matrix, increases cohesion strength and tightness. Rheological properties of the compositions vary with the concentration of these filling agents.

We used the method of mathematical calculation of the density of packing of the polyfraction loose mixture with simultaneous allowance for the character of interaction of the hybrid polymeric matrix with an inert inorganic surface [8]. This made it possible to solve the following problems: determine the ratio between different fractions of inert filling agents in the polyfraction mixtures, which provided the optimal degree of packing with the highest density and Young modulus; establish the maximum possible doses of the filling agents in the polymeric matrix, which did not prevent formation of the glued-mechanical joints produced by different methods; and provide simultaneous interaction of the glue interlayer and riveting in shear tension with the adhesion-cohesion character of fracture.

Two compositions of HGC were selected, having no effect on the process of formation of the clinch- and TOX-joints. Shear tests of the single-spot glued-mechanical joints showed that the use of GKK-1 increased strength of the clinch- and TOX-joints 1.5 times with simultaneous fracture of the glue interlayer and «button». The use of GKK-2 insignificantly increased strength of the mechanical joint. Fracture of specimens occurred in series — first the separation of the glue interlayer took place to form strands, and then shear or pullout of the «button» followed (Figure 6). Fracture of the glue layer was of a cohesion character. High adhesion strength is indicative of high sealing properties and crevice corrosion resistance.

Figure 7. Appearance of pneumatic press for formation of mechanical joints

The investigations conducted resulted in the development of the principles of design of the punch–die system for clinch- and TOX-joints on deep-drawing thin-sheet steel, as well as stationary equipment on the C-frame base with the pneumatic actuator and adjustment of compression in a range of 0–20 kN (Figure 7). The technology for formation of mechanical and glued-mechanical joints produced by the punching method is recommended for manufacture of assemblies of thin-sheet vehicles operating in corrosive environments.

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