THE ANNALS OF “DUNAREA DE JOS” UNIVERSITY OF GALATI
FASCICLE V, TECHNOLOGIES IN MACHINE BUILDING,
ISSN 2668-4829 (PRINT) 2668-4888 (ONLINE)
https://doi.org/10.35219/tmb.2025.1.09

JOINING METHODS FOR ALUMINIUM SHEETS

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ABSTRACT

Aluminium and its alloys can be joined using various mechanical methods, by adhesive bonding, by welding, or through hybrid (combined) methods. This paper briefly presents methods for joining sheets and flat bars with overlapping edges, including traditional methods such as riveting, resistance spot welding, and cold spot welding. Furthermore, recent techniques such as cold welding on cogged edges, self-piercing riveting, hybrid joining by welding and self-piercing riveting, and cold spot welding with an interlayer, developed in our laboratories are addressed.

KEYWORDS: pressure welding, aluminium joints

1. INTRODUCTION

Aluminium and its alloys can be joined using various mechanical methods, adhesive bonding, welding, or hybrid methods. Welding can be carried out either by fusion or by pressure. Fusion welding involves localized melting at the contact areas of the components, with or without filler metal, the joint being formed upon solidification. Pressure welding is based on bringing the peripheral atoms of the components close enough into the range of mutual attraction forces to restore interatomic bonds.

2. JOINING BY RIVETING

Riveting is a mechanical joining process for steel components, initially and especially used in shipbuilding. It is known that the largest riveted structure was the Titanic, for which three million rivets were used. For productivity reasons, during World War II, riveting was replaced by welding in the fabrication of the 4,500 DWT Liberty ships. These vessels were built in Miami (USA) at a rate of one ship every 8 weeks, compared to 8 months by riveting, and were used in convoys to transport American aid to the Allied countries. In Romania, riveting was replaced by welding at Galați Naval Shipyard after 1965.

Riveting of aluminium components was used on an industrial scale in the last century for manufacturing small and medium-sized aircraft. The method has low productivity and a high cost. A further disadvantage is the creation of stress concentrators, which can lead, over time, to cracking starting from the rivet holes.

3. RESISTANCE SPOT WELDING

This process is defined **as resistance pressure welding**, performed by conduction, in which two or more overlapping parts are clamped between contact electrodes, and the weld is formed at the faying surfaces in places through which the electric current passes [1].

Spot welding began to be widely used in the production of Ford automobiles with steel sheet bodywork after 1930. Figure 1 shows the macrostructure of a weld nugget obtained by the soft welding of low-carbon steel sheets with a thickness of 5 + 5 mm. The thermo-mechanically affected zone and the electrode imprints can be observed. Using hard welding, these imprints are smaller.

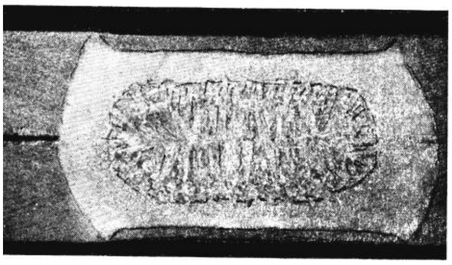


Fig. 1. *Macrostructure of a welded spot*

The dimensions of the fused nugget directly influence the mechanical strength of the joint. The recommended dimensions are: for nugget diameter: $d_n = 2s + 3\ mm$ and for nugget height: $h = 1.4s$. A correctly executed spot weld joint breaks near the weld, at the periphery of the weld nugget, by pulling the nugget out of one of the sheets.

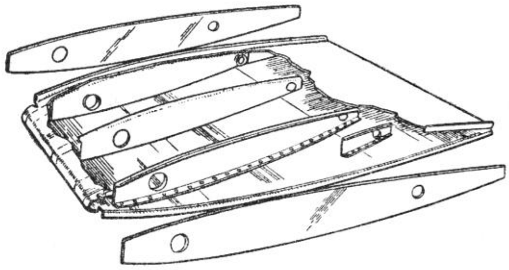


Fig. 2. *Aircraft wing (detail)*

The excellent results obtained by applying spot welding in automobile manufacturing (a car body requires approximately 10,000 spot welds) led to applying this process in aircraft construction as well (Fig. 2). The number of spot welds in the construction of a large passenger aircraft today exceeds 500,000. Pressed or profiled components made of aluminium alloys up to 2 mm thick are joined. In the peripheral areas of the fuel tanks integrated into the wings, seam welding is applied instead of spot welding to ensure tightness.

Aluminium and its alloys show both high electrical and thermal conductivity and a higher expansion–contraction coefficient than carbon steels. For this reason, welding aluminium requires specific equipment capable of providing very high current densities ($j = 1000...1500\ A/mm^2$) and very high specific electrode force ($160...220\ N/mm^2$), and also a synchronized variation of these parameters. Spot welds located in highly stressed zones are radiographically tested, and defective ones are repaired by drilling and inserting explosive rivets.

4. COLD PRESSURE WELDING

Cold welding is applied to sheets with thicknesses of 0.2…15 mm, overlapped and locally pressed using punches generally circular. For bilateral deformation (Fig. 3a), two punches are used, producing symmetrical deformation of both components or a unilateral deformation (Fig. 3b) can be done, where one punch is used, producing an aesthetically better surface on one side of the joint. It is also possible to weld two or more sheets of equal or different thicknesses (Fig. 3c).

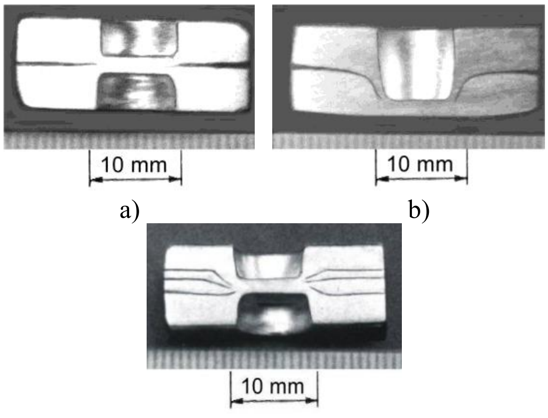


Fig. 3. *Macroscopic aspect of aluminium specimens welded by cold pressure welding*

The spot size influences the mechanical strength of the joint. For the punch diameter, the recommended value is $d = (1...3)s$, ensuring sufficient metal flow in the joint cross-section (a factor responsible for breaking and removing the oxide film in the welded zone). A correctly executed joint breaks near the weld, at the periphery of the spot, by pulling the nugget out of one of the sheets.

The deformation scheme (unilateral or bilateral) also influences the mechanical strength of the joint. Subjectively, one might assume that the joint in Fig. 3b should withstand higher shear breakage loads compared to the one in Fig. 3a, due to the additional mechanical anchoring provided by the unilateral punch imprint. In reality, the shear strength decreases (Fig. 4) because of material thinning caused by stretching over a larger distance. In the case of sheets of different thicknesses, strength reduction occurs only when unilateral deformation is applied from the thinner sheet side, and the reduction is more pronounced when the sheet is thinner (Fig. 4). If deformation is applied from the thicker sheet side, the shear strength increases.

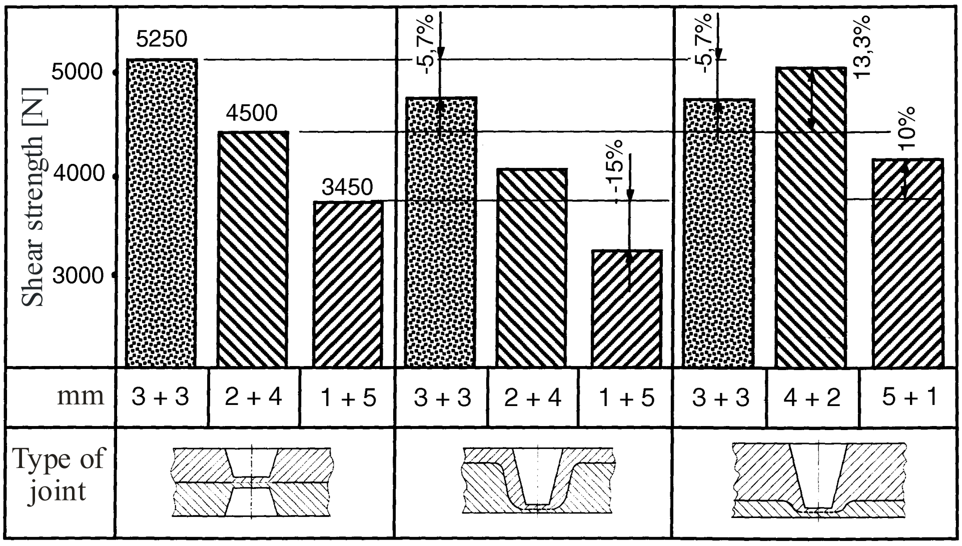


Fig. 4. *Shear strength for different assemblies of Al 99.5 sheets using punches with diameter d = 8 mm*

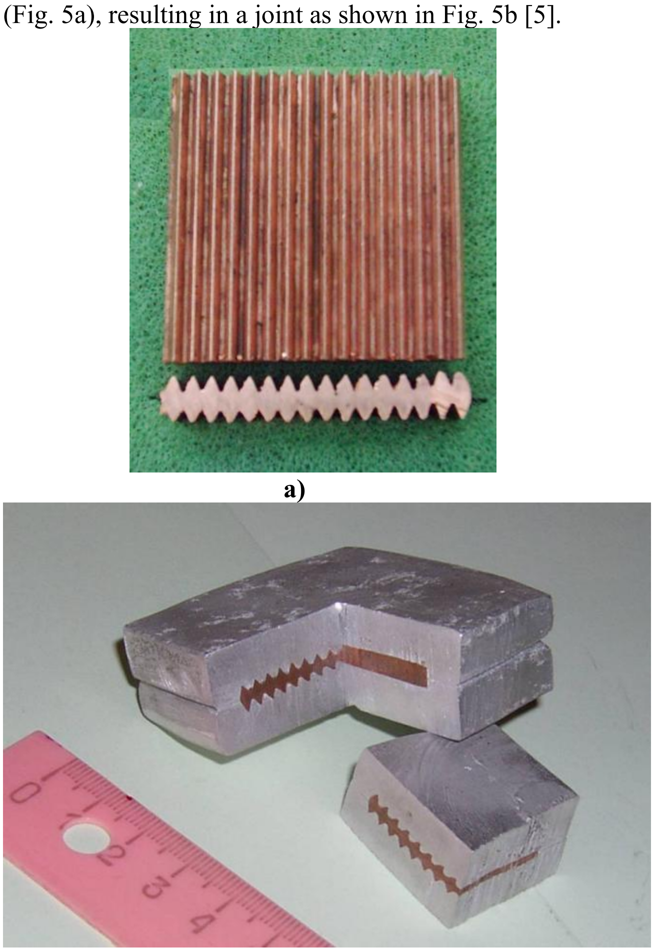
The cold spot welding process has the obvious disadvantage of producing deep imprints due to the significant plastic deformation required — over 70% in the case of aluminium — to achieve solid-state bonding. The nugget thickness and its mechanical strength are reduced compared with a fusion spot weld. For this reason, the process is mostly recommended in the electrotechnical field, where electrical contact quality is prioritized.

A first important application of cold spot welding, with major economic impact due to the elimination of copper, was the welding of aluminium connectors in electrical substations for the Trans-Siberian Railway in the former Soviet Union. Aluminium flat bars with cross-sections between 5 × 60 mm and 10 × 100 mm were welded in 4–5 spots, enabling the conduction of currents up to 18,000 A.

5. COLD PRESSURE WELDING ON COGGED EDGES

Welding on cogged edges represents a new, original variant of cold pressure welding. A component made of a softer material (typically aluminium) is welded to a harder component that has serrations. Under pressure, the softer material flows along the serration slopes and fills the interspaces, bringing the peripheral atoms of the components within the range of mutual attraction. The sliding action breaks the non-metallic layer locally and forms isolated bonding nodes, typical of grip welding**.** The main advantage of this method is the possibility of achieving cold welding with a reduced degree of deformation, only 20–30% [4].

We propose the cold joining of aluminium flat bars used in electrical control and supply stations by means of this new welding process. A double-serrated copper interlayer is inserted between the flat bars (Fig. 5a), resulting in a joint as shown in Fig. 5b [5].



a)

b)

Fig. 5. *Cold welding on cogged edges of aluminium flat bars:* ***a)*** *interlayer element;* b) *aspect of the joint.*

Experiments show that serrated-surface welding is superior to cold spot welding because it avoids cross-sectional reduction, increases mechanical strength by about 2.5 times, and enlarges the electrical contact area by about 15 times.

6. SELF-PIERCING JOINING

To simplify the assembly of structures made of light alloys (including automotive bodies), new methods of mechanical joining similar to riveting, but without local perforation or with the joining element being directly driven into the material without pre-drilling. This process is also mentioned among other advanced joining techniques.

The joining sequence is shown in Fig. 6, where during the first step, an embossment is created (deep drawing), and in the second step, after the lower punch is lifted, the embossment is deformed, thereby locking the components together. Considering the final shape of the deformed embossment (similar to the head of a rivet), the process can be called self-piercing joining.

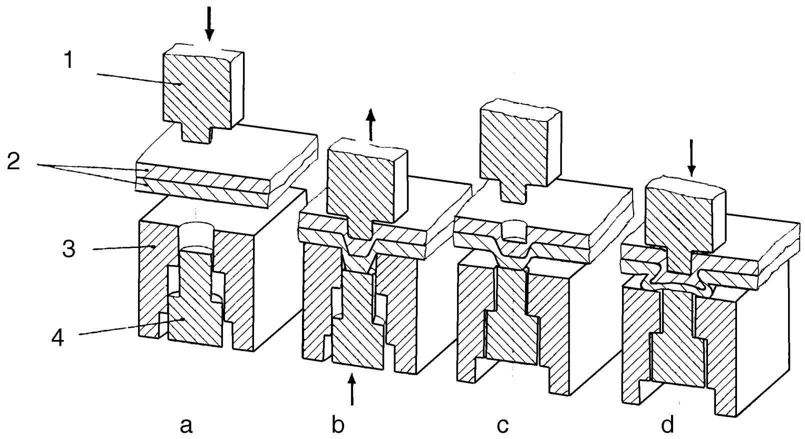


Fig. 6. *Mechanical joining by riveting without local perforation: a – initial position; b – embossing; c – lifting of lower punch; d – riveting (self-piercing riveting); 1 – upper punch; 2 – sheets to be joined; 3 – base plate; 4 – lower punch.*

The authors specify that this type of joint in AlMg5Mn sheets of 1.25 mm thickness performs better under variable loading than a fusion spot weld, but also that resistance to breakage is halved.

7. HYBRID COLD SPOT WELDING WITH SELF-PIERCING JOINING

On close observation of Fig. 6, one notes the similarity between the pressing equipment and technology used here and those used in cold spot welding with concentric punches. This demonstrates the compatibility of the two technologies and their potential to complement each other to increase joint strength.

We therefore propose cold welding of the mechanically riveted zone from the previous method. This is achieved by pre-cleaning the faying surfaces in the spot area and by adjusting the stroke of the upper punch so that the final distance between punches is $\Delta = (0.2\ldots0.3)(s_1 + s_2)$. This results in 70–80% deformation, sufficient to produce cold welding in aluminium alloys.

The hybrid process — cold spot welding combined with self-piercing joining, using coaxial punches — is shown in Fig. 7, with stages: a – clamping, b – free embossing, c – lifting, d – welding + riveting, e – flattening.

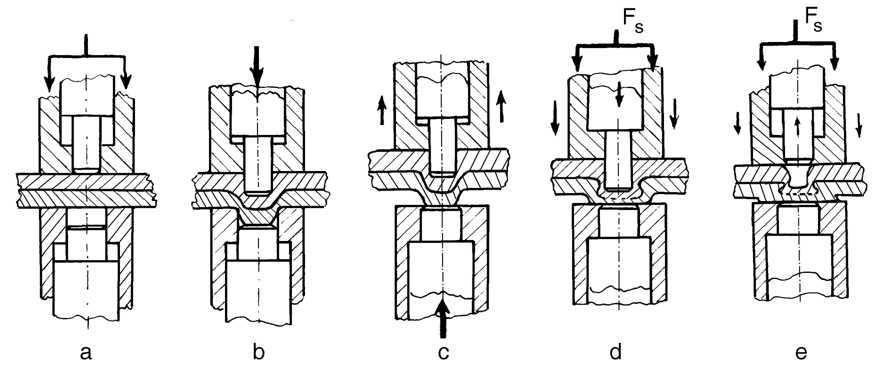


Fig. 7. *Cold spot welding combined with self-piercing joining, using coaxial punches*

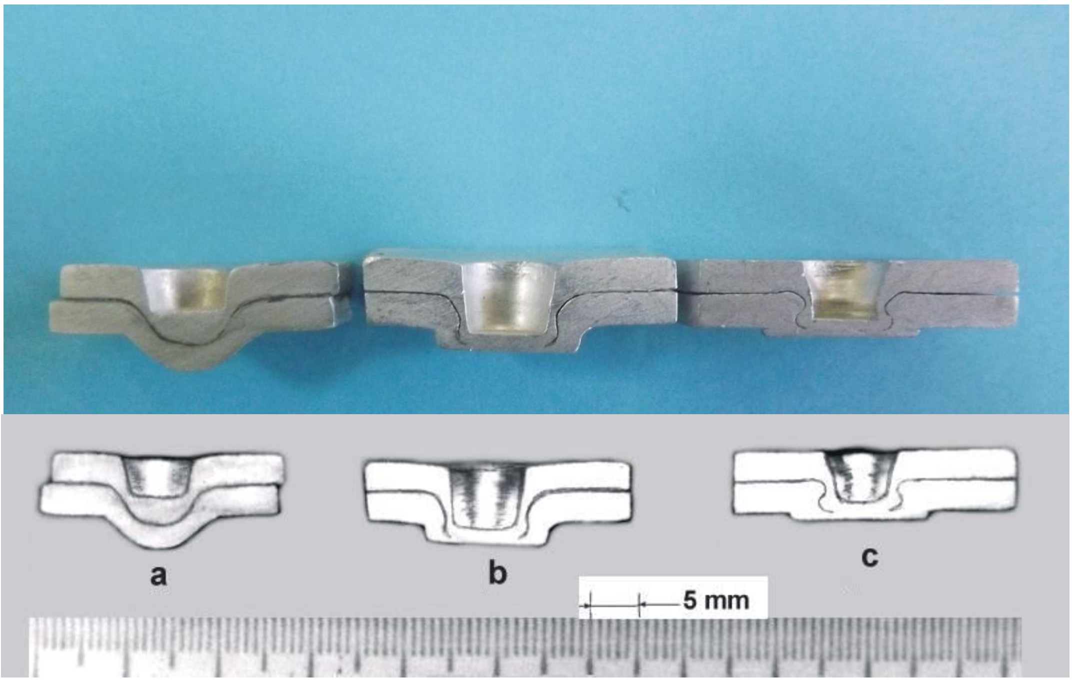


Fig. 8. *Macroscopic aspect of specimens after execution stages: a – free embossing; b – welding + riveting; c – flattening*

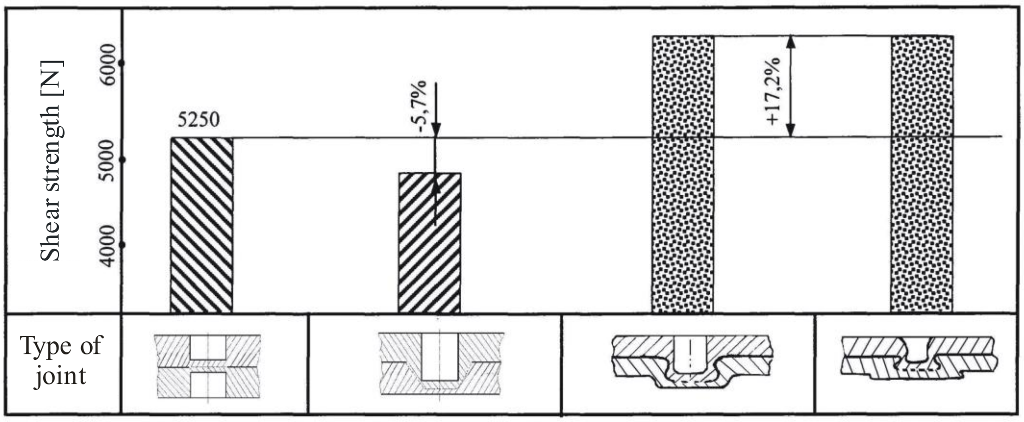


Fig. 9. *Shear strength of cold spot welded joints vs. welded + riveted joints, with or without additional flattening*

In our laboratory, we performed practical tests by joining aluminium sheets (99.5% purity), 3 + 3 mm thick, using punches with a diameter of 8 mm. The exact flow and deformation of the material can be seen in the macroscopic images in Fig. 8. The separation line in the unwelded areas is clearly visible due to excessive etching in a 20–30% caustic soda solution of the sectioned and polished samples.

Shear tests showed that the mechanical strength of joints obtained by the combined riveting + welding process is higher than that of joints welded only by cold spot welding (Fig. 9). Compared with simple unilateral cold spot welding, the increase in strength reaches 25%. This improvement is explained by the embedding of the upper sheet into the lower one and by the thickening of the peripheral zone of the weld, where fracture occurs.

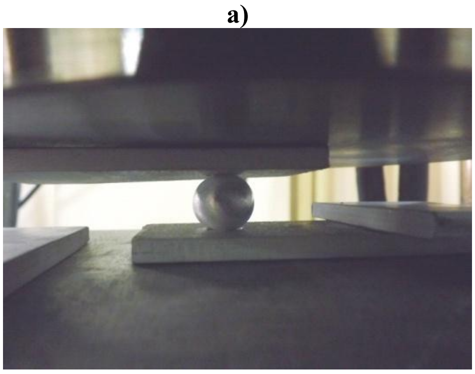
8. COLD PRESSURE WELDING WITH INTERMEDIATE METAL

Our aim is to avoid the formation of deep indentations characteristic of cold pressure spot welding. The objective is to weld aluminum busbars of 5 mm and 10 mm thickness, used in electrotechnical applications for energy transmission and distribution. As the intermediate element, spherical balls of 99.5% electrotechnical aluminum, of the same composition as the busbars, were used. The spheres were machined from solid bar stock, leaving a small connection at one end (Fig. 10. a). This connection was cut off after mechanical cleaning with a rotary brush made of stainless steel wire, which was carefully degreased before use.

Instead of the punches used in conventional spot welding, flat pressing plates were used, as shown in Figure 10b. To highlight the materials in the welded zone, the sectioned test bars were immersed in a caustic soda solution of 20–30% concentration and excessively etched (15–25 minutes) for improved visualization.

Several assembly variants were carried out, with different methods of busbar preparation.

a)



b)

Fig. 10. *Preparation of the spherical intermediate element and pressing with flat plates*

8.1. Welding with flat plates

In the simplest version, an aluminium spherical insert (serving as the nugget core) is introduced between the sheets to be welded, as shown schematically in Fig. 11a. Through the application of pressure, the sheets come into intimate contact, the sphere flattens, and partially deforms the plates in the contact zone (Fig. 11b).

The joint cross-section resembles the fusion nugget characteristic of resistance spot welds under pressure. Externally, the welded area appears as a circular mark with a diameter corresponding to that of the flattened spherical insert between the sheets (Fig. 11c), due to the strain hardening of the material in the weld zone and the intensification of metal flow. When subjected to shear testing, failure occurs by detachment of the flattened sphere from one of the sheets (Fig. 11d).

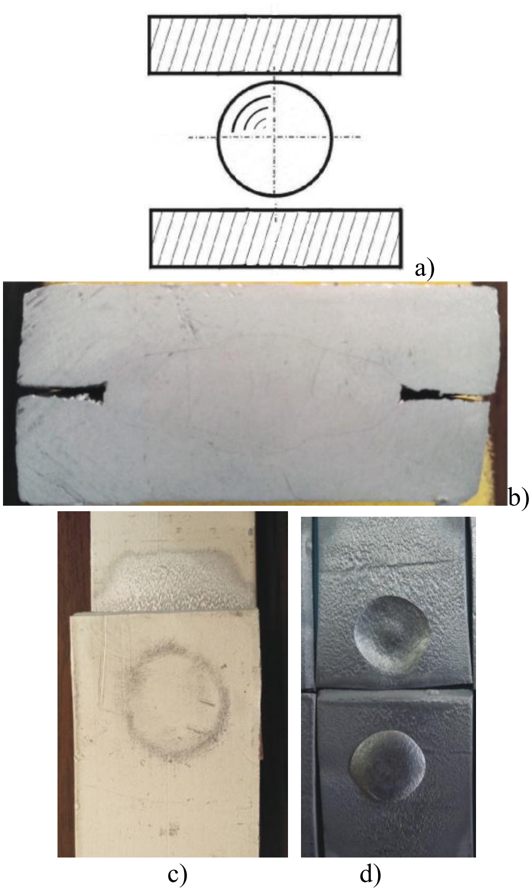


Fig. 11. *Cold welding with flat plates and a spherical intermediate element*

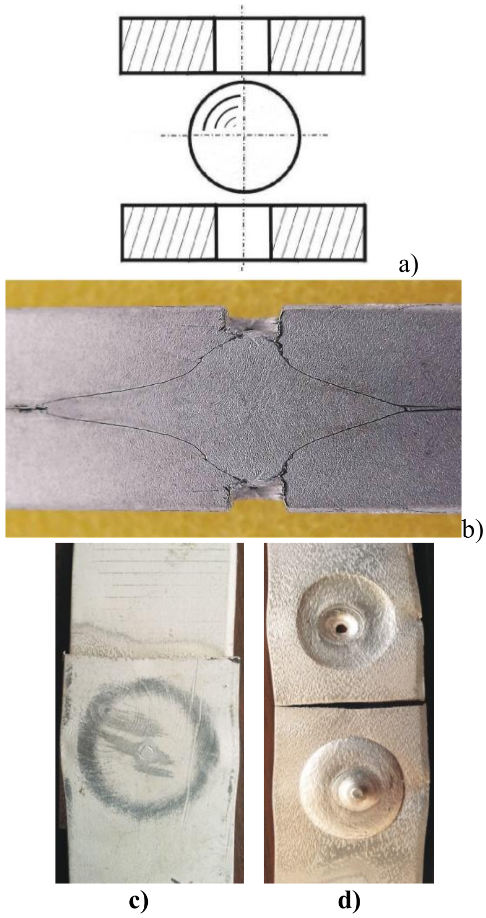


Fig. 12. *Cold welding with perforated plates and a spherical intermediate element*

8.2. Welding with Drilled Plates

For precise positioning of the plates, and also to facilitate metal flow and create an additional mechanical anchoring pin, holes of d = 5 mm were drilled into the flat bars, as shown schematically in Fig. 12a. In the cross-section (Fig. 12. b), we can see the penetration of the spherical insert metal into these holes, which is also evident from the external appearance of the joint (Fig. 12. c). When subjected to shear testing, the joint fractured by detaching from the intermediate metal of one of the aluminium plates (Fig. 12. d).

8.3. Welding with perforated and countersunk plates

To enhance the flow of the deformed metal from the intermediate sphere, the 5 mm diameter holes were machined with a conical countersink on the sphere side, as shown in Fig. 13a. An aluminum sphere with a diameter of 14 mm was used. The diameter was selected so that the ratio between the sphere volume and the hole volume was 2:1, ensuring a deformation degree of 50%. Improved metal flow was observed, completely filling the holes in cross-section (Fig. 13. b), as confirmed by the external appearance of the joint (Fig. 13. c). Fracture occurred by pull-out of the intermediate metal from one of the plates (Fig. 13. d).

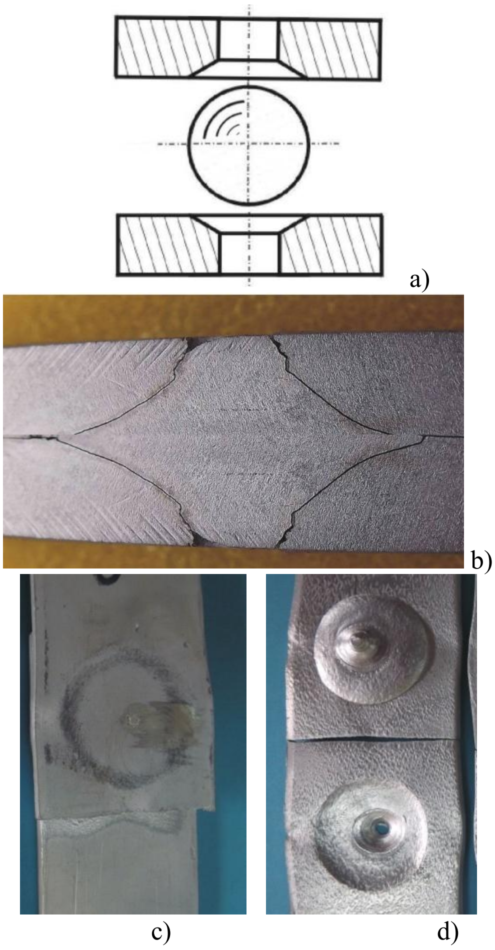


Fig. 13. *Assembly with perforated and countersunk plates*

8.4. Welding with perforated and double-countersunk plates

To achieve a self-riveting effect, the 5 mm diameter holes were machined with 10 mm conical countersinks on both sides (Fig. 14a). During deformation of the intermediate sphere, the work-hardening of the metal produced a lateral displacement of the busbar material, which flattened the external surface and effectively canceled the upper countersink (Fig. 14b). Examining the joint surface in Fig. 14c, two concentric circles can be observed: the inner one, 5 mm in diameter, formed by the sphere metal filling the hole, and the outer one, 10 mm in diameter, formed by the flattening of the busbar countersink.

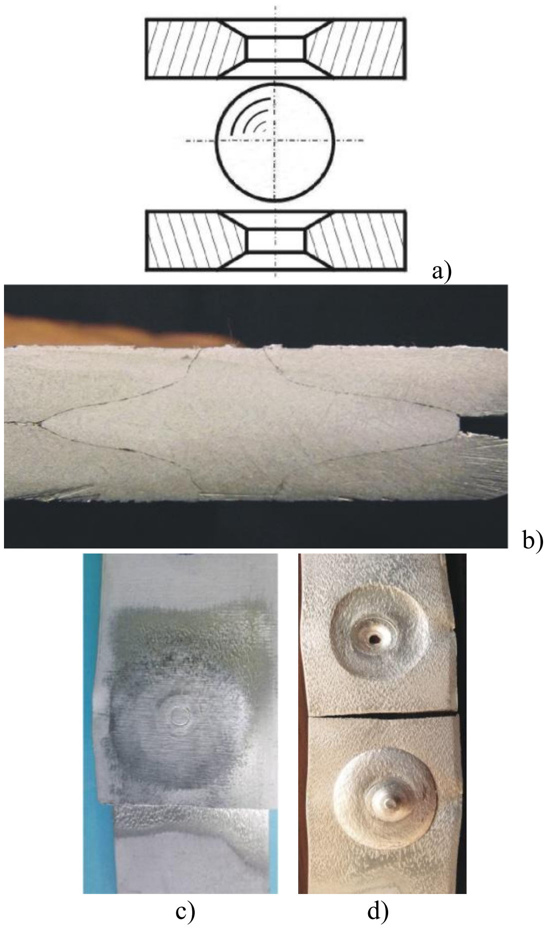


Fig. 14. *Welding with drilled and double-countersunk plates*

The test results show that it is impossible to obtain the desired rivet-like head when using metals with identical or similar plasticity. The intermediate metal should have significantly higher plasticity and lower deformation resistance than the base aluminium plates in order to achieve self-riveting.

A major advantage of this method compared to conventional spot welding is the increase in current-carrying cross-section for electrical networks. For example, with 5 mm aluminium flat bars, in the classical case with 80% deformation, the current is confined to approximately 1 mm along the nugget perimeter. Whereas when using the spherical insert, the effective contact area can reach a diameter of up to 25 mm.

Another advantage compared to conventional resistance spot welding is the elimination of deep electrode indentations, resulting in a smooth, flat surface in cases where an aesthetic joint is required.

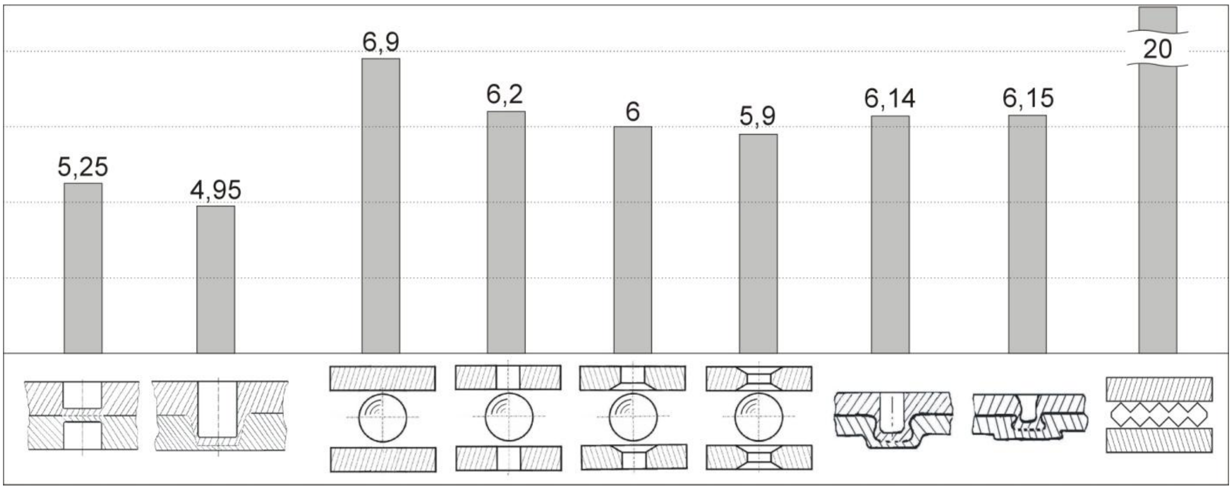


Fig. 15. *Shear strength of various cold pressure spot welds [kN]*

9. CONCLUSIONS

Aluminium sheets and their alloys can be joined by different methods, which vary in productivity, cost, specific equipment, and in the characteristics of the resulting joints (appearance, mechanical strength, electrical conductivity, or corrosion resistance). Therefore, it is important to know these methods in order to select the most appropriate one for the specific requirements of the intended product.

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