MODERN METHODS OF WELDING ALUMINIUM ALLOYS TO STEELS (Review)

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Modern methods of welding aluminium alloys to steel were analyzed. Techniques of minimizing the thickness of intermetallic interlayer in the joints were noted, which include heating of the joint metal below the steel melting temperature, accelerated cooling of the joint, and application of damping coatings or inserts.

Keywords: *welding processes, aluminium alloys and steels, welded joints, intermetallic interlayer, technological techniques, heat input, hybrid welding, electron beam welding*

Designers and architects in their work continuously face the dilemma of high strength and low weight. It can be solved by a combination of strong and lightweight materials. In particular, joining steel and aluminium elements became widely applied in automotive industry and shipbuilding, in manufacture of passenger railway cars, as well as lightweight building structures and decorative elements of facades. Here such material qualities as strength and corrosion resistance, low weight and good formability are combined.

In automotive industry the tendency of steel replacement by aluminium alloys emerged as far back as 25 years ago. It was calculated [1] that lowering of car weight by 100 kg saves on average 0.3 l of petrol per 100 km of mileage. In addition, at lowering the car weight and respective lowering of energy power input the European norm for 2012 — CO_2 emissions of not more than 130 g/km — can be met [2]. By the data of [3], the potential weight saving when aluminium is used instead of steel is up to 42 %. However, actually, this figure drops to 24 % as a result of application of modern high-strength steels. In mass production of cars, steel ensures a weight saving, and considering its good formability and strength, it remains one of the most important materials in automotive industry.

European car makers undertook to reduce the consumption of pigments that led to a change of design of the body of Audi A2 and A8, in which it is equal to almost 24 % of the car weight [4]. So, in the modern car individual parts, or even whole assemblies, as for instance, engine compartment in BMW, are made of aluminium. In Audi TT only the rear part of the body is steel, the rest is made of aluminium alloy (Figure 1).

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In shipbuilding steel replacement by aluminium alloys allows reducing the ship weight and lowering the center of gravity, and further gives such important advantages as nonmagnetization and corrosion resistance. Aluminium alloys are used to make hull structures (predominantly, of lightweight ships), as well as superstructures, deck cabins, bridges, chimney casings, partitions, enclosure, etc. [5]. Aluminium alloys also found broad application in manufacture of railway rolling stock. In Europe aluminium alloys are used to make about 80 % of railway cars [6].

Automotive industry mostly uses alloys of Al–Mg–Si system of 6000 series with good hot painting properties (preserve strength properties at heating up to 300 °C) [6]. In Europe readily formable EN AW 6016 alloy (%: 1.0–1.5 Si; ≤ ≤ 0.25–0.60 Mg; ≤ 0.2 Mn; ≤ 0.5 Fe; ≤ 1.15 Ti; balance being Al) is mostly used for body outer parts, in the USA these are alloys ANSI 6111 (0.9 Si; 0.7 Cu; 0.2 Mn; 0.7 Mg; balance being Al) and 6061 (0.6 Si; 0.23 Cu; 0.15 Mn; 1.0 Mg; 0.2 Cr; balance being Al) [6]. Alloys of Al–Mg system with 2–3 % Mg are now used for support frames of cars and other parts made with application of arc welding [7].

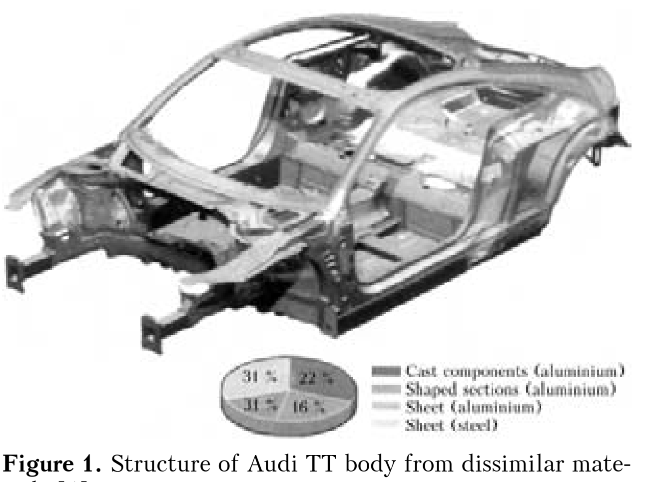

Figure 1. Structure of Audi TT body from dissimilar materials [4]

It is known that the main obstacle in joining steels to aluminium alloys is a negligible (0.025 at.%) solubility of iron in aluminium. The problem arises at formation of brittle intermetallic phases of various composition, both at interaction of liquid metals, and as a result of element diffusion at joint heating up to temperatures of 350–400 °C, i.e. below aluminium melting temperature. Noticeable thickness of intermetallic layer has a negative role already at joint cooling because of a considerable difference in the coefficient of thermal expansion (1.2 and 2.3 mm/100 °C for steel and aluminium, respectively), leading to appearance of significant inner stresses and quite often to formation of cracks. High hardness of intermetallic layer (up to HV 1200) and low viscosity of chemical compound of metals prevents relaxation of thermal stresses.

Most of the problems, related to welding of aluminium alloys to other metals, and methods of their solution are described in [8]. However, over the 30 years, which have passed since the moment of its writing, welding science and technology proposed a number of technological processes, which took us closer to satisfying industry requirements when making hybrid joints of steel and aluminium. Some of them are described in this review.

It was already mentioned above that the influence of brittle intermetallic zone is the smaller, the thinner it is. In keeping with [9, 10], the thickness of this zone should not be greater than 10 μm. It is obvious that such a thickness can only be ensured by limiting the heating of the joint butt. All the modern processes are based on observing this condition.

Arc welding. In manufacture of steel-aluminium parts great attention is given to traditional welding processes in their new implementation.

Nonconsumable electrode welding of joints of steel with aluminium alloys is currently seldom applied, although there are reports [11] about good results at application of DC05 steel (C ≤ ≤ 0.06, Mn ≤ 0.35) 0.8 mm thick with EN AW 6016 alloy 1.15 mm thick. Blanks of 9.5 mm diameter demonstrated reduction ratio of 7.9. At greater deformation ratio, cracks develop, which initiate in aluminium.

Considerable progress has been made in consumable electrode inert-gas arc braze-welding (MIG). Braze-welding of steel to aluminium, based on a significant difference of melting temperatures of aluminium (~660 °C) and steel (~1500 °C), allows making from aluminium alloy side a welded joint with solidified filler metal, and a brazed joint from the steel side. Here the process, naturally, should be conducted so that the part was heated above the aluminium alloy melting temperature but below steel melting temperature.

The simplest form of joints made by consumable electrode braze-welding are overlap joints. Here the aluminium alloy part is located from the consumable electrode side, and the steel part is predominantly heated due to heat removal from the aluminium part. In [11] it is shown that at removal of the arc axis for 3 mm from the aluminium part edge, it is possible to reduce intermetallic phase formation to the thickness of 2–3 μm in the weld central part and to less than 1 μm on the boundary. To achieve optimum properties of butt and overlap joints weld reinforcement, as well as the extension should correspond to 2.5 times thickness of the sheet. Static strength of such a joint is on the level of the weakest partner. Steel wettability by aluminium is improved by applying zinc coating on steel that was noted already by V.R. Ryabov in 1969 [12]. Liquid aluminium dissolves zinc [13].

Influence of filler material composition on characteristics of braze-welded joint of aluminium and steel was studied by many experimenters. These investigations included testing wires from Zn- and Al-based material [10]. It is shown that application of wire from a zinc alloy makes more complicated the task of filler feed and controlling welded joint geometry, because of low hardness and melting temperature of the material. At the same time, with this filler wire type, thickness of intermetallic phase layer decreased and corrosion resistance of the joint increased. As a result, AlSi3Mn1 wire was recognized to be the best composition. The same metal was used also in investigations [11], the results of which are given above. Earlier [14] high-silicon wire from AlSi12 eutectic alloy was used as filler material. However, the small difference between AlSi12 melting temperature (577 °C) and zinc evaporation temperature (907 °C) requires an extremely accurate heat input into the weld, in order to avoid zinc evaporation from the steel surface and joining pure steel to aluminium with formation of Fe_2Al_5 or $FeAl_3$. Silicon ability to slow down intermetallic phase formation was also taken into account here [12, 13].

At present AlSi3Mn1 filler material is applied in cold metal transfer (CMT) welding developed by Fronius Company [2, 15, 16]. System of control of short-arc process ensures an almost no-current transition of filler material to the base

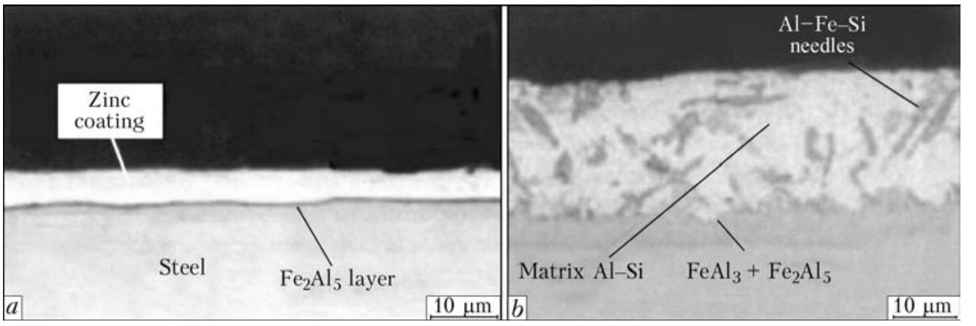

Figure 2. Microstructures of joints of aluminium to steel with zinc (*a*) and alumosilicate (*b*) coatings

aluminium alloy, and the melt wets the Zn-plated steel. This process is innovative not only in that owing to highly accurate control of short-circuiting current, heat input can be lowered, but also in that a good drop transfer of molten metal takes place due to a periodical change of the direction of consumable wire motion, and welding without spatter can be implemented.

Braze-welded joints from DC05 steel with zinc coating of 140 g/cm^2 0.8 and 1.0 mm thick and AW 6061-T4 alloy, the thickness of which varied from 1.15 up to 1.20 mm, were tested. AlSi5 alloy was used as filler material and welding was performed in pure argon. Both the sheets were located in one plane, and misalignment by height was not more than 0.35 mm along the butt. Static strength of the joint was equal to base metal strength, and at steel thickness of 0.8 mm the joint failed in steel, whereas at steel thickness of 1.0 mm it failed in the aluminium alloy HAZ. In the first case calculated rupture strength was 190 MPa (base metal ultimate strength was 210 MPa in aluminium alloy and 280 MPa in steel), and in the second case — 210 MPa. In the produced joints average thickness of the intermetallic fringe on top, bottom and along the end face of the sheets was not more than 5 μm, which the paper authors believe to be not critical.

Coating of steel sheet surface has an essential influence on weld geometry. Five different coatings were checked, namely zinc, nickel, titanium, alumosilicon and alumozinc [3]. Heat-resistant coatings from titanium and nickel are partially or completely preserved after joining. Titanium alloy completely prevents formation of brittle Fe–Al phases [17], but requires an increased heat input, thus creating high weld reinforcement above the steel surface, impairing the conditions of item formability.

Nickel coating also prevents intermetallic phase growth. Application of fluxing means enabled improvement of wettability of the steel part surface and obtaining a flat geometry of the weld. All the joints with nickel coating failed in the base material of aluminium sheet at testing.

In case of alumosilicate coating, which allows working without the fluxing means, a highly uniform intermetallic phase forms of average thickness of 5 μm. As noted by the authors of [3], such a coating has no advantages over hot galvanizing; it, however, creates readily wettable surfaces and smooth transition from the weld to the steel sheet that markedly improves the mechanical indices.

Microphotographs of the joints of aluminium to steel and different coatings obtained by CMT method [10] (Figure 2) reveal the diffusion nature of intermetallic layer formation.

One of the methods to produce a satisfactory steel-to-aluminium joint can be steel coating by copper so that aluminium bronze was produced from the aluminium side at pulsed welding in inert atmosphere [18].

Lowering of heat power density applied to the butt was achieved in inert-gas arc butt welding at the pressure of 600–1000 Pa, when joining steel-aluminium pipe transition pieces in cryogenic mechanical engineering [19, 20]. A feature of this process is the diffuse shape of the arc, as well as relatively low temperature of the cathode and its intensive evaporation at temperatures not exceeding than the melting temperature at atmospheric pressure by more than 100–300 °C. This enables making joints by braze-welding schematic without any significant manifestation of diffusion of the metals being joined.

In many structures, where arc welding cannot be successfully replaced by more «delicate» processes, steel and aluminium are joined using bimetal transition pieces, produced by various processes, which are considered below.

Laser welding. At present this process is becoming ever wider applied in mass and batch production not only when making miniature joints, but also extended welds in automotive industry. Considering the possibility of fine control of thermal power of pulsed laser radiation, researchers have also given their attention to this fusion welding process for joining steel to aluminium.

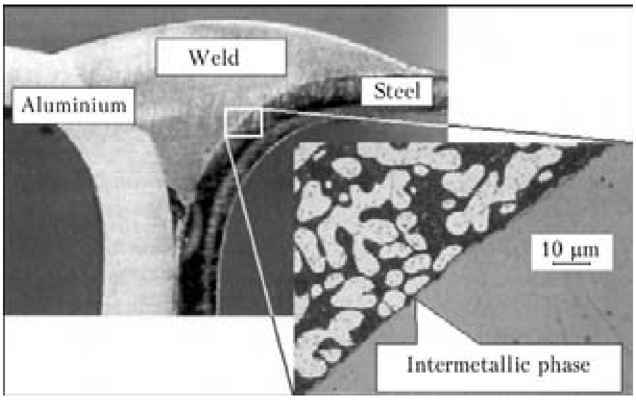

Figure 3. Schematic of laser braze-welding in car manufacture [23]

When making overlap joints, heating by neodymium laser is performed from the steel side [21]. The steel sheet is heated up to aluminium melting temperature, while remaining solid. Static strength of such joints reaches 70–90 % of aluminium strength. Similar to consumable electrode welding, the joint is of braze-welded nature.

Strength of laser braze-welded joints can be increased through application of Al-based filler metal and preheating of the steel Zn-plated sheet by the second laser beam to improve the wettability of the surface by molten filler [22]. At static tensile testing, the overlap joint failed through the aluminium sheet. Thickness of intermetallic fringe on the steel sheet did not exceed the critical value (Figure 3). Corus RD & T Company (The Netherlands) called such a process Fluxless Laser Brazing [23].

Developers of the technology of joining steel to aluminium can see great advantages of hybrid laser-arc welding (Figure 4). Increase of the speed of CMT process at leading laser heating allows minimizing intermetallic phase formation and joint zone embrittlement [4]. However, in this case the need for good heating of steel for its sufficient wettability and lowering of heat input to avoid the growth of intermetallic phase come into a conflict. Bremen Institute for Applied Beam Technology (BIAM) managed producing butt joints of up to 3 mm sheets with 140 MPa strength by selection of modes of CO_2 laser radiation and MIG welding [24].

Speed of welding 1 mm thick butt joint at 4 kW laser power was more than 100 mm/s [25].

Process of hybrid laser-arc welding became accepted in manufacture of special bimetal tanks and items in automotive industry and shipbuilding [17]. At simple bending the characteristics of such joints are not critical, but at deep drawing they are not quite satisfactory so far.

Another kind of hybrid welding, namely laser welding with pressure application (Figure 5) has a special place, combining the advantages of fusion welding and pressure welding [26]. In particular, interface temperature can be controlled by scanning with the beam. The joint forms during strip compression by rollers.

In the experiment with 1 mm strips of A6061 alloy (wt.%: 0.8–1.2 Mg, 0.4–0.8 Si, balance being Al) with more than 295 MPa ultimate strength and cold-rolled sheet steel SPCC (< 0.12 C, 0.5 Mn, < 0.04 P, < 0.045 S) with 270 MPa ultimate strength the laser beam was guided between the strips being welded, which were taken through rollers, and scanned from one surface to another or just over one surface parallel to the joint line. This technique allowed controlling the butt metal composition and largely suppressing formation of brittle intermetallic compounds using the thermal cycle of fast beam heating and abrupt cooling at pressing to-

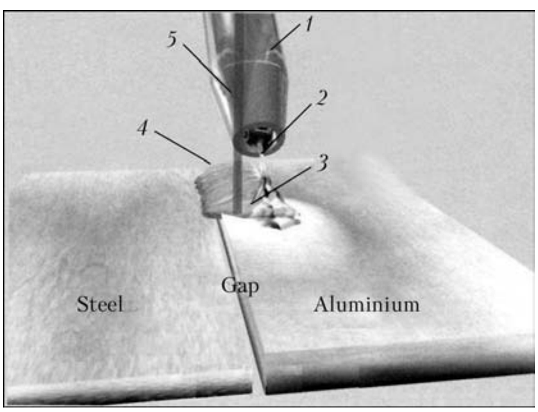

Figure 4. Schematic of hybrid laser-arc welding [17]: *1* — welding torch; *2* — filler wire; *3* — weld pool; *4* — weld; *5* — laser beam

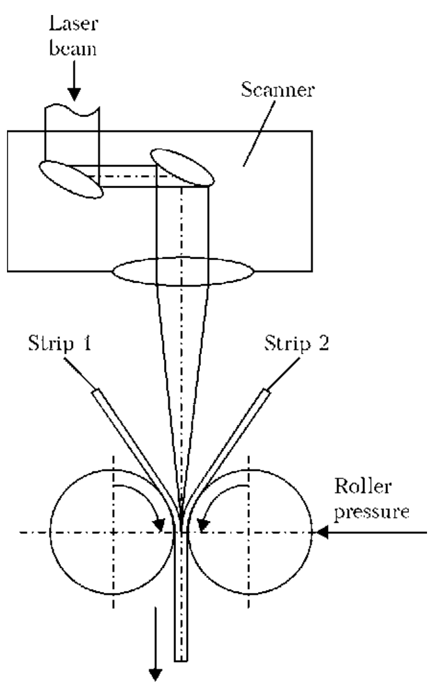

Figure 5. Schematic of laser-press welding

gether by rollers [27, 28]. At irradiation of sheet joint from the ferrous metal side melting of aluminium alloy occurs by heat transfer [26]. Investigation of the above joints [29] showed that they have sufficient strength, and can be used in manufacture of the car bonnet and roof.

Overlap joint of galvanized steel and aluminium alloy, made by roller laser welding at beam power of 1200–1400 W and roller pressure of about 3 kN [30], failed in the aluminium sheet at shear testing. Thickness of intermediate layer between steel and aluminium was from 7 up to 20 μm. During electron microscopy examination [31] it was established that the main phase in the intermediate layer was Al–Zn solid solution. Intermetallic compounds FeAl, Fe_2Al, Fe_4Al_{13} and $Fe_2Al_5Zn_{0.4}$ were found in it by electron diffraction. The authors came to the conclusion about heating of the strips being welded above the melting temperature, while strength of the joint with relatively thick intermetallic layer is determined by formation of Al + Zn phase with finely-dispersed intermetallic inclusions.

Electron beam welding. Sound joints of aluminium and steel parts were achieved at application of buffer coatings of titanium [18], nickel and zirconium [32] on steel.

Resistance spot welding. In resistance spot welding, similar to all the above-considered processes, joining occurs at simultaneous solidification of molten metal of the parts being joined. Generally known and earlier mentioned causes do not allow producing a satisfactory spot joint of steel and aluminium alloys even in welding in capacitor-type machines with stiff discharge mode [33].

The solution was found due to application of an intermediate bimetal strip produced by simultaneous rolling of steel and aluminium [34]. In welding two separate nuggets form on aluminium-aluminium and steel–steel interface. Limitation of heat input allows avoiding diffusion formation of the intermetallic layer on the inner boundary of bimetal insert. Static and dynamic testing of such joints showed that the strength of spot joints is comparable with riveted joints.

Press welding. This welding process was studied for the case of joining aluminium buses with steel elements of electrolyzer current conduit for aluminium production [35]. To reduce the probability of intermetallic compound formation, the authors used additives of finely dispersed powders of silicon, copper or zinc, which ensured development of an eutectic phase with melting temperature below that of aluminium melting. The lowest thickness of intermetallic interlayer was achieved at application of silicon powder. The highest breaking stress was also observed in this case — 55–60 MPa.

Diffusion welding. Despite the fact that the joining process proceeds without melting of the parts being joined, because of the long time of contact of materials being welded at a high temperature, aluminium diffusion into steel leads to formation of brittle intermetallic phases rich in aluminium ($FeAl_3$ and Fe_2Al_5) [36].

Explosion welding. Bimetal joints produced by explosion welding are used extensively in the shipbuilding yards of Japan, Poland, USA, Great Britain, France and other countries, as was already mentioned above, as an intermediate element welded by the known processes (already in the similar combination) to the base material of the structure. The state-of-the-art limits application of steel-aluminium sections of a simple shape with 120 MPa strength [24].

12Kh18N10T stainless steel (wt.%: ≤ 0.12 C; 17–19 Cr; ≤ 0.8 Si; 1–2 Mn; 9–11 Ni; up to 0.02 S; up to 0.035 P) was successfully welded to AMg6 alloy (5.8–6.8 Mg) by explosion through an intermediate AD1 commercial alloy layer [37, 38]. The boundary between AD1 and stainless steel did not have any typical indications of intermetallics, although $FeAl_3$ and Fe_2Al_5 phases were actually found. Tearing stress was also equal to 120 MPa.

Results of testing welding of steel-aluminium hull structures with application of bimetal transition pieces allowed RSI of Structural Materials «Prometey» (St.-Petersburg) developing technological recommendations on welding butt, tee and overlap joints in manufacture of small displacement surface vessels, satisfying the requirements made of ship-hull materials [5].

Friction welding. Friction welding of pure aluminium A0 to St.3 (0.14–0.22 C; 0.3–0.6 Mn) and 1Kh18N9T (≈ 18 Cr; ≈ 9 Ni) steels of 16 and 20 mm diameter already 50 years ago [39] demonstrated the possibility of producing satisfactory welded joints owing to forging, which leads to pressing out of possible reactive phases of aluminium and steel (during welding the rubbing surface of aluminium is in the molten state) and bonding of pure surfaces of base metals. This was also shown by observations in electron and X-ray radiation [40].

Weldability of aluminium alloys with steel by friction directly depends on the alloy hardness. So, AMg6 alloy practically does not weld to steel by friction, whereas AMg3 alloy forms quite satisfactory joints with steel [41].

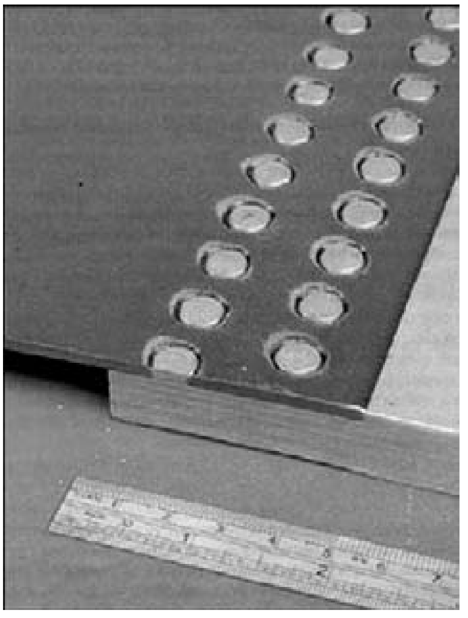

Figure 6. Example of joining steel and aluminium sheets by stir-lock process

The limitations of traditional friction welding also include the requirement of cylindrical shape of at least one of the parts.

Now, friction stir welding (FSW) process turned out to be quite suitable for welding sheets [42].

In FSW of spot welds of A5052 aluminium alloy and low-carbon steel, despite the relatively low temperature of steel heating (below aluminium alloy melting temperature) a layer of intermetallics was found between the metals been joined [43]. However, the shear strength of the joint was relatively high. Steel coating by zinc increased the strength, if the latter was pressed out of the joint zone [44].

A good result was obtained in FSW of aluminium alloy to stainless steel [45]. In the transition zone a layer of intermetallics was also found, but its thickness was limited to just several micrometers.

FSW and CMT processes were compared under JOIN B1 project [46] in welding aluminium to steel. Examination of metallographic sections by energy-dispersive X-ray spectroscopy showed that in all the spot welds, similar to welds made by CMT, joining takes place through an intermetallic phase. In welding by Fronius method this phase had a very non-uniform thickness, while in FSW the thickness was almost unchanged. It, actually, greatly depends on position relative to tool axis. Near the tip the intermetallic phase thickness is relatively small (2.5 μm) and at a distance it reaches 12 μm. FSW process was patented by TWI in 1991. Over the recent years they also developed stir-lock process [47], the principle of which is clear from Figure 6.

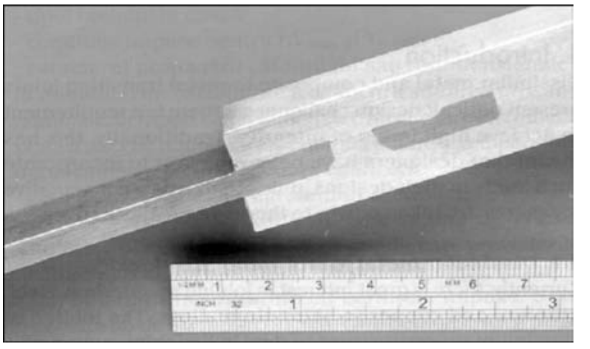

Figure 7. Locking a perforated steel sheet in the aluminium one by stir-lock process

In the harder material (this is steel in our review, but the process was successfully tried out for joining aluminium to magnesium, titanium and copper) a counterbored hole is made, through which the soft metal is heated by a rotating tool. Heated metal is pressed into the hole under pressure, creating a head in the free cavity of the steel sheet, similar to a rivet head.

With stir-lock process the joint can also be made using perforated inserts, as shown in Figure 7.

This review did not cover the processes of joining steel to aluminium by simultaneous deformation, namely rolling, extrusion, drawing, etc., as they are quite traditional and well-known to the reader.

CONCLUSION

As shown by this review of modern processes of welding aluminium alloys to steel it is not possible to completely avoid formation of an intermetallic interlayer between the metals being joined with the processes using thermal transformation of metals. However, in technological terms it is possible to create conditions, under which the thickness of this interlayer will be minimum, and its influence on joint characteristics will, thus, be noncritical. Such welding techniques include joint heating below the steel melting temperature (braze-welding), accelerated cooling of the joint and application of intermediate damping coatings or inserts. Finally everything is determined by the value of heat input, or, in other words, heating temperature and time during which the parts are staying at high temperature.

Percussion capacitor-type welding can be an example of successful welding of aluminium wire to steel plates [48]. With this process metal of materials being joined, heated up to melting temperature, is removed at upsetting, and at cooling rate reaching 10^6 K/s, joint temperature decreases so fast that interdiffusion of metal through the joint boundary is practically absent.

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