FLUX ARC BRAZING OF ALUMINIUM TO GALVANISED STEEL

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The study was dedicated to investigation of the processes occurring in DC flux arc brazing of overlap joints between thin-sheet aluminium and galvanised steel. Aluminium AD1, galvanised steel 08Yu, and reactive flux of the $KF-AlF_3-K_2SiF_6-KZnF_3$ system were used in the experiments. It was shown that reactive flux of the K–Al–SiF system used for brazing without passage of the filler alloy through arc gap improves conditions of formation of the overlap joints (wetting, spreading and filling of capillary gaps by the aluminium-silicon filler alloy) between aluminium and galvanised steel due to rapid destruction of the oxide film and formation of layers of low-melting point metal melts in the brazing location due to reactions of the flux with the materials being brazed. It was found that in brazing under conditions of arc heating the rate of spreading of the filler alloy on galvanised steel is approximately 3 times as high as on aluminium. The non-equilibrium contact angle on galvanised steel is 28–33°, and on aluminium — 8–10°. The data are given on structure of the brazed joints, composition of individual phases and chemical heterogeneity of the joints. According to the X-ray spectral microanalysis results, the 2–5 μm thick variable-composition Al–Fe–Si system transition layer containing small amounts of manganese (from steel) and zinc (from coating) forms at the contact boundary with steel. It was shown that the brazed joints between alloy AD1 and galvanised steel 08Yu produced by using the aluminium-silicon filler alloy have strength equal to that of the aluminium alloy. The overlap joints tolerate bending to an angle of 180°, while in multiple inflections (5–6 times) fracture occurs in aluminium. 23 Ref., 2 Tables, 5 Figures.

Keywords: *aluminium, galvanised steel, arc brazing, reactive flux, spreading of filler alloy, reaction layer, brazed joints*

Reduction of weight of structures with simultaneous improvement of their mechanical characteristics is one of the key challenges in building of low-consumption and reliable flying vehicles and ground-based equipment. Thin-sheet aluminium–steel structures are characterised by high design strength and corrosion resistance. They are 2 times as light as the steel ones, and are applied under severe conditions of alternating loads, temperatures and aggressive environment. An example is motor car construction, where decrease in weight allows extending service life, achieving substantial saving of fuel, and diminishing the negative effect on the environment. One of the main ways of reducing weight of a car body is application of high-strength ultralow-carbon steels [1] with aluminium or zinc corrosion-resistant coatings, and aluminium alloys. Meeting this challenge involves a number of complicated problems. Steel and aluminium differ greatly in their physical-mechanical characteristics (melting point, thermal expansion coefficient, strength) and chemical properties (ultimate solubility of iron in solid aluminium corresponds to 0.03–0.05 at the eutectic temperature [2, 3]), this leading to certain difficulties in providing the strong joints.

Solid-state welding of aluminium alloys to steel by the explosion [4] and friction [5] methods finds a limited application because of specifics of thin-sheet structures. In the fusion welding processes, interaction of steel with aluminium in the liquid phase is a cause of formation of a transition layer consisting of brittle intermetallic phases of the Al–Fe system, low strength, porosity and cracking of the welded joints. To avoid formation of solidification cracks in welding of 3–4 mm thick sheets, the content of brittle phases in the weld pool should not exceed 10 wt.% [6]. Alternatives to fusion arc welding can be the modern processes of TIG welding [7], laser welding [8, 9], modified MIG braze-welding (CMT-process) [10–12] with local melting of aluminium, or high-temperature brazing (laser brazing [13], MIG process [14], constricted arc process [15]), which are characterised by decreased heat input. Low level of the thermal-deformation effect in the brazing location, owing to a low heat input, and high corrosion resistance of the joints due to preservation of the zinc coating are the main advantages of arc brazing. The causes preventing a wide application of arc brazing for fabrication of strong sheet structures are related primarily to difficulties in ensuring a high quality

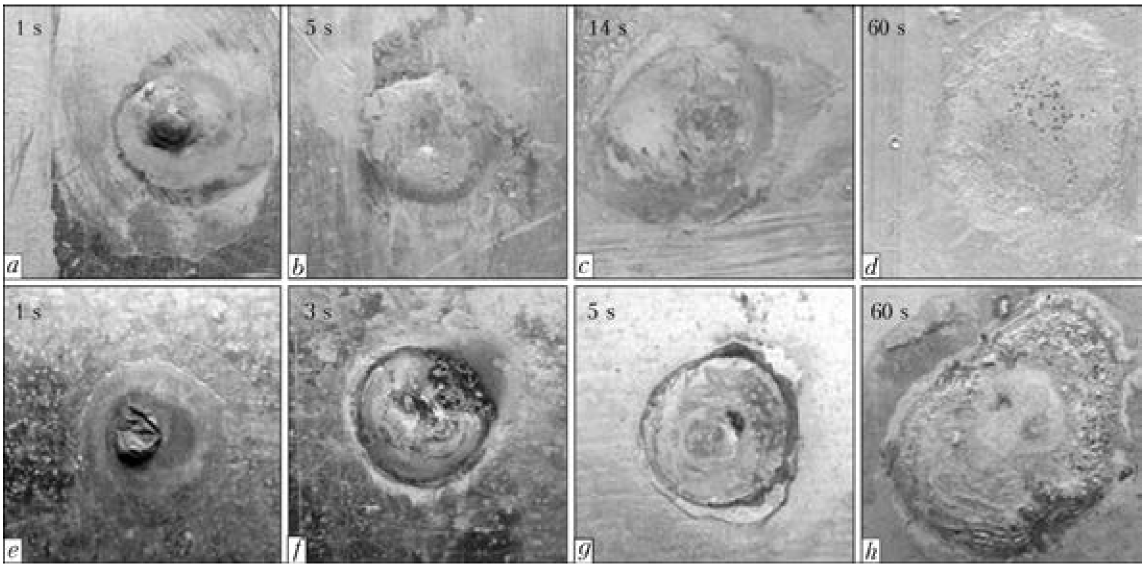


Figure 1. Drops of solidified filler alloy Al–12Si on aluminium AD1 (*a–d*) and galvanised steel 08Yu (*e–h*): *a–d* — AD1; *e–g* — 08Yu (arc brazing in argon atmosphere, I_b = 25 A, T_b = 600–615 °C, Kemppi system MASTERTIG MSL(TM) 2300 ACDC (Finland)); *h* — steel (furnace brazing in nitrogen atmosphere, T_b = 600 ± 3 °C)

of the joints. This can be achieved by using welding machines with feedback and low heat input [16].

Aluminium filler alloys of the Al–Si system are used for different types of the joints (overlap, T-, butt joints) between galvanised sheet steel and aluminium. In spreading of aluminium [17] or aluminium-silicon melts [18] on carbon steel, the transition layer of the Al–Fe–Si metal system forms as a result of reaction diffusion at the contact boundary, inhibiting spreading and leading to its complete termination. At the same time, it is a known fact that in high-temperature brazing of aluminium [19] and its alloys to stainless steel [20, 21] the reactive mixtures of the KF–AlF_3 salt system, containing additions of potassium hexafluosilicate and potassium-zinc fluoride, actively destroy (dissolve) oxides and form (from reduced silicon and zinc contained in fluorides) a layer of low-melting point alloy Al–Si(Zn) on aluminium, which improves spreading and capillary properties of the finished filler alloy.

Activation of the processes of wetting, spreading and improvement of capillary properties of the aluminium filler alloys can also be achieved in arc brazing due to the use of reactive fluoride fluxes of the KF–AlF_3 salt system. In this study, the experiments were carried out by using non-corrosive flux FAF 540 developed by the E.O. Paton Electric Welding Institute [22].

Under the TIG process conditions, wetting of the materials being brazed (aluminium AD1 and galvanised steel 08Yu) with a liquid filler alloy and reactivity of flux FAF 540 of the KF–AlF_3–K_2SiF_6–$KZnF_3$ salt system were evaluated from the area of spreading of the filler alloy addition (with weight of 0.17 g) of aluminium-silicon alloy (Al–12 % Si). The argon-arc torch was placed at the centre of a sample, so that the arc was ignited on the filler alloy addition. The brazing temperature range of 600–615 °C was set by the values of the straight polarity direct current and holding time. The rate of feeding of a shielding gas (argon of grade A) to the brazing zone was 6–9 l/min.

Substantial differences in physical-chemical properties of aluminium and steel, presence of a zinc coating on steel, local heating, and short-time interaction of liquid and solid phases during the brazing process exert a considerable effect on spreading of the filler alloy.

It was established that at the relatively equal time ranges and arc heating parameters the speed of motion of perimeter of a filler alloy drop and, hence, the area of spreading of the filler alloy on galvanised steel are higher than those on aluminium (Figure 1).

The kinetics of spreading of the filler alloy is related to the complex processes of chemical interaction of the salt and metal melts at the contact boundary with aluminium and galvanised steel. Destruction of the surface oxide film (as a result of chemical interaction with the salt melt) and distribution of the filler alloy over the overheated (approximately by 200 °C higher than the melting point) zinc melt improve wetting with the liquid filler alloy and its spreading on galvanised steel. In this case, fluidity of the filler alloy changes but insignificantly in dissolution in it of the entire coating metal. According to study [23], fluidity of aluminium alloys with 7–11 % Si and 8–15 % Zn is identical to that of commercial silumins, and their mechanical properties are higher and depend on the zinc content, whereas formation of the Al–Fe–Si metal system transition layer at the interface with steel, as noted above, inhibits and stops spreading of the filler alloy.

The maximal area of spreading of the filler alloy on the surface of galvanised steel is S_{sp} = = 540 mm^2 during time t = 5 s at the set arc heating parameters (current I_b = 25 A, voltage $U_b = 12 \pm 0.3$ V). At the same brazing parameters the comparable area of spreading (S_{sp} = 560 mm^2) of the filler alloy on aluminium can be achieved at a longer (about 3 times) time and a local penetration of this material (Figure 2).

At a constant intensity of heat transfer of the heat source, because of high thermal diffusivity and heat capacity of aluminium, more heat is required to provide the equal area of spreading of the filler alloy compared to steel. Under non-isothermal conditions, spreading of the filler alloy on aluminium is restricted to region of existence of a thin layer of the metal melt over which the filler alloy is distributed. Therefore, the area of spreading of the filler alloy in non-equilibrium arc heating is much smaller (see Figure 2) than during the equilibrium process of brazing in furnace with a high uniformity of the temperature field and maximum permissible temperature gradient of ±5 °C over the aluminium part. The non-equilibrium contact angle on galvanised steel is 28–33°, and that on aluminium is 8–10°.

The most common type of joints on thin-sheet structures of aluminium and galvanised steel are the overlap joints. Mechanical properties of this type of the joints increase with increase in overlapping (edge lapping) of the thin sheets, and with improvement of the quality of filling the gap with the filler alloy and obligatory formation of fillets of a concave shape. Flux arc brazing of the overlapped aluminium to galvanised steel samples was performed on the 1 mm thick sheets with a set edge lapping of 2–6 mm. Filler wire AK12 and non-corrosive flux FAF 540 were used

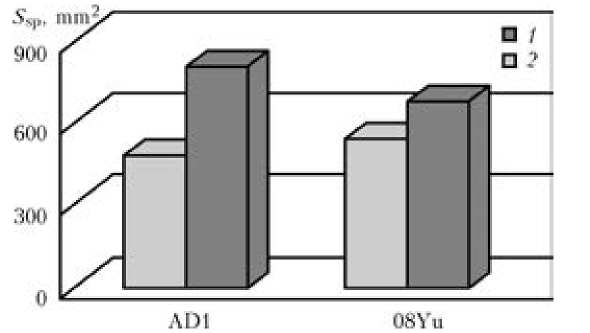


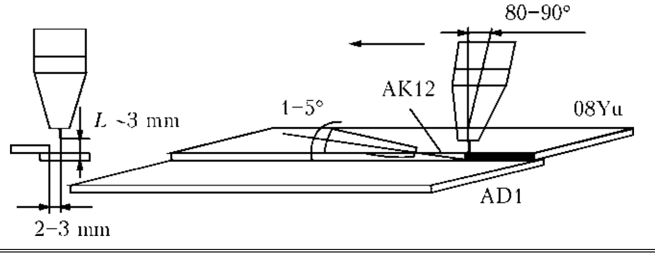
Figure 2. Area of spreading S_{sp} of filler alloy of the Al–12Si system in flux arc (*1*) and furnace (*2*) brazing

as brazing consumables. The aluminium sheets before brazing were subjected to etching in water solutions of alkali (15 % NaON) and a mixture of acids (2 vol.% HF and 20 vol.% HNO_3), and the steel sheets were degreased with acetone. A layer of flux (50 % water suspension) was applied to the aluminium sheet at the brazing location. Brazing of the overlap joints between aluminium and galvanised steel was carried out on the preliminarily prepared sheets. The effect of the arc brazing parameters was evaluated from the quality of formation, microstructure and chemical heterogeneity of the seams, tolerance of the brazed samples to bending to an angle of 180° and inflections, and tensile strength of the brazed joints at room temperature.

Investigations of straight polarity direct current flux arc brazing of aluminium to galvanised steel allowed defining the optimal parameters for the process of formation of the overlap joints (Table 1).

Characteristic peculiarity of the arc brazing procedure is ignition of the short arc and guiding it over the melt of a thin reaction layer on the surface of aluminium at a distance of approximately 2–3 mm from the joint, which makes it possible to diminish the thermal effect on the materials being brazed and retain integrity of the zinc coating. The filler wire is fed ahead of the arc at sufficiently small angles, so that it is melted in a thin layer of the metal melt. Optimal conditions of formation of the brazed seam are

Table 1. Approximate parameters of flux arc brazing of thin-sheet (1 mm) aluminium AD1 to galvanised steel 08Yu

D_f, mm	I_b, A	U_b, V	v_b, mm/s	TIG process flow diagram
1.6	47–50	9–11	12.0	
1.2	24–26	8–10	1.5–2.0	

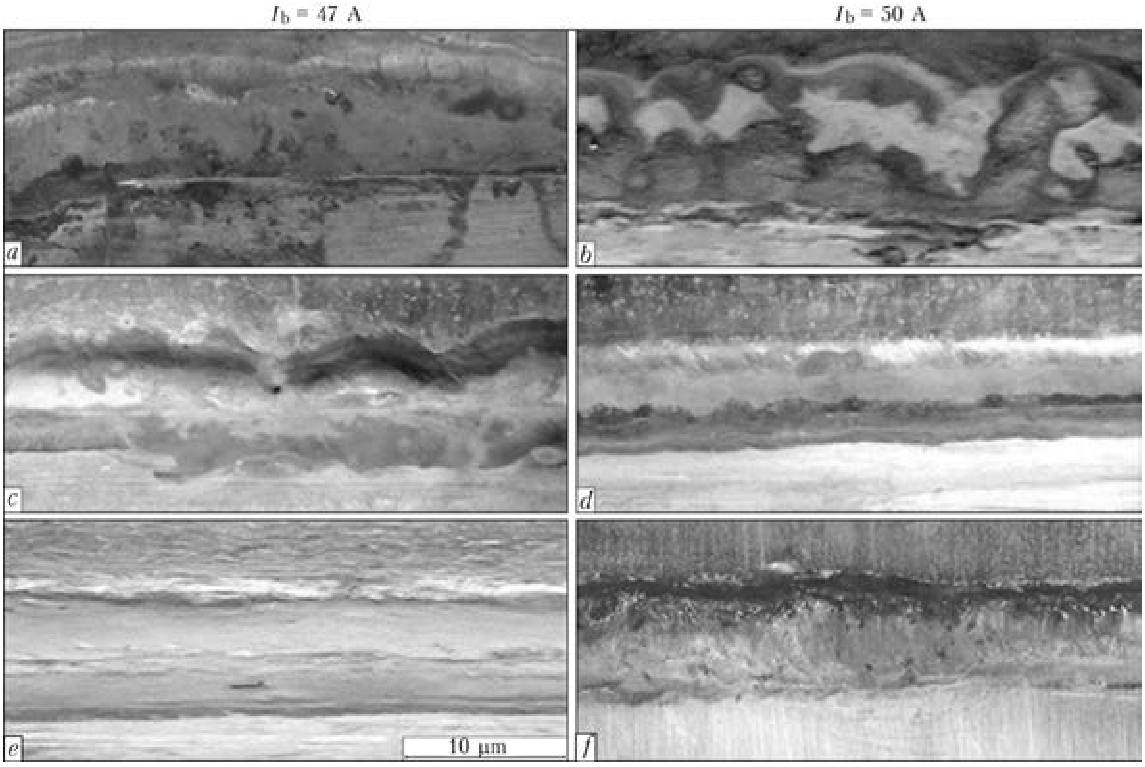


Figure 3. Appearance of the joints (×2) between galvanised steel 08Yu and aluminium AD1 produced in arc brazing (v_b =12 mm/s: *a*, *b* — excess of flux (G_f = 30 g/m^2); *c*, *d* — shortage of flux; *e*, *f* — optimal flux consumption (G_f = = 7–10 g/m^2)

achieved in melting of the filler in a relatively small volume of molten metal of the reaction layer, spreading of the excessive melt into the zone of a higher temperature and rapid filling of the brazing gap under the effect of capillary forces. This critical condition provides the stable process of formation of the brazed joint at the identical temperatures maintained at edges of the sheets of the materials joined. Reliability of shielding during the brazing process is ensured at a flow rate of the A grade argon equal to 8–10 l/min and torch nozzle diameter of 10–12 mm.

To ensure good formation of the seams (Figure 3, *a*, *f*) the consumption of flux is strictly limited and chosen depending on the brazing parameters.

Violation of the stable process of melting of the filler wire related to a change in the con-

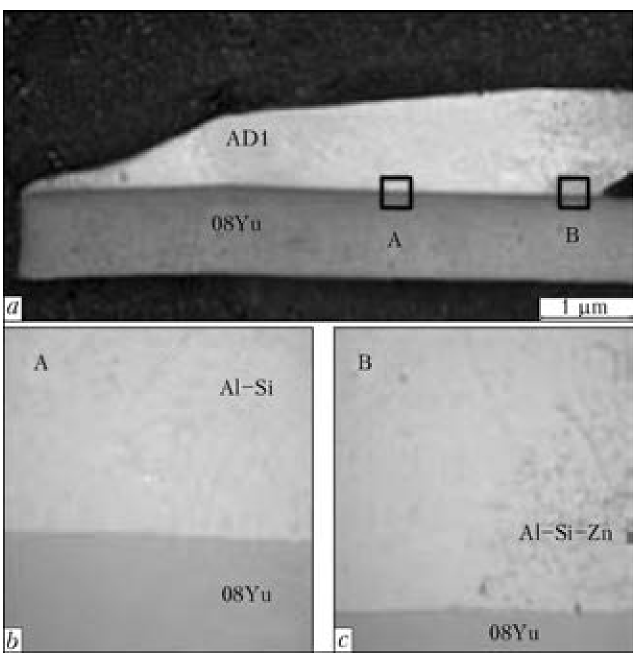


Figure 4. Macro- (*a* — ×10) and microstructure (*b*, *c* — ×400) of the brazed joint between aluminium AD1 and galvanised steel 08Yu

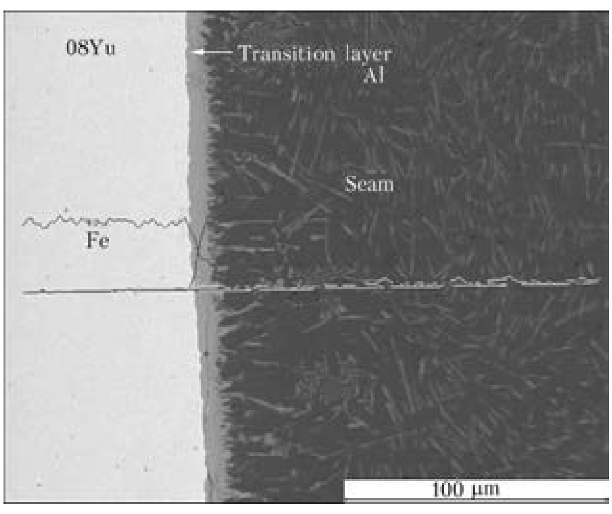


Figure 5. Microstructure (×350) and distribution of elements in the brazed joint of aluminium AD1 to galvanised steel 08Yu (microscope CamScan)

Table 2. Content of elements (wt.% in microvolumes) in the brazed joint between alloy AD1 and galvanised steel 08Yu

Joint region	Al	Si	Mn	Fe	Zn
08Yu	–	–	0.32	99.68	–
Transition layer (~5 μm)	65.58–59.93	5.11–4.75	0.12–0.09	29.20–34.89	0–0.35
Seam (matrix)	93.57–94.30	4.56–4.04	–	1.39–1.24	0.48–0.42

sumption of flux (deviation from the optimal consumption) leads to a non-rational distribution of the filler alloy in the brazed joint: rolls of metal onto the edge (Figure 3, *a*, *b*), lacks of penetration (Figure 3, *c*, *d*) and other defects of the brazed joints. The overlap steel-aluminium joints produced by arc brazing at the optimal parameters are characterised by complete filling of the variable gap with the filler alloy at a lap width of 5–6 mm. In this case the brazed seams are usually of a segmented shape and have a smooth surface and smooth transitions to aluminium and steel (Figure 4). On the reverse side of the joint (fillet region) the filler alloy forms a concave meniscus with a radius of less than 0.5 mm. The smooth surface of the seam with smooth fillets leads to decrease in the concentration of stresses, which is particularly important for making rigid structural connections on the above dissimilar metals.

The brazed joints between aluminium AD1 and galvanised steel 08Yu produced under non-isothermal conditions (TIG process, I_b = 24 A, v_b = 1.5 mm/s) have a heterogeneous structure (Figures 4 and 5).

The contact boundary with aluminium is meandering, having traces of a deep (about 180 μm) intergranular penetration of the eutectic phase (Al + Si) into the aluminium alloy being brazed. The central part of the seam is occupied by the aluminium-based α-solid solution with the lamellar dispersed eutectic (Al + Si) located in its interlayers between the grains (in Figure 4, *a* — gray cells, in Figure 5 — light cells). Investigation of chemical composition of the fillet (Figure 4, *c*) revealed the trend to alloying the brazed seam with zinc (formation of alloy of the Al–Si–Zn system) and growth of its content to 20 wt.% in the peripheral regions bordering with the zinc coating. According to the results of X-ray spectral microanalysis, the variable-composition Al–Fe–Si system transition layer from 2 to 5 μm thick, which contains small amounts of manganese (from steel) and zinc (from the coating), forms at the contact boundary with steel (Figure 5; Table 2).

No diffusion porosity and flux inclusions were detected in the transition layer region and in the aluminium to galvanised steel brazed joints. Marked structural changes in steel were not revealed either.

The overlap brazed joints tolerate bending to an angle of 180°, and in multiple inflections (5–6 times) the fracture occurs in aluminium. Tensile tests at room temperature showed that the brazed joints between alloy AD1 and galvanised steel 08Yu produced by using the aluminium-zinc filler alloy have strength equal to that of the aluminium alloy.

Conclusions

1. Reactive layers of the melts (aluminium-silicon and zinc) provide substantial improvement of capillary properties of the filler alloy, thus making it possible to join thin-sheet aluminium to galvanised steel with a large (up to 6 thicknesses) overlap.

2. The investigation results allowed establishing the arc brazing parameters that provide rapid destruction (dissolution) of oxides, stable melting, spreading and complete filling of the gap with the filler alloy.

3. The 2–5 μm wide intermetallic layer of the Al–Fe–Si system forms under non-equilibrium conditions at the contact boundary with steel. Zinc in the brazed seam is contained mostly in the aluminium solid solution.

4. As shown by the short-time shear tests, the overlap brazed joints have strength equal to that of the aluminium alloy.

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NEWS

Technology of Slag Crust Utilisation in Pipe Welding

Technology of flux waste processing after welding was developed, which includes separation with subsequent return of unused flux into production and manufacture of AN-60SM flux from the slag crust. Technology of flux manufacturing from the slag crust does not envisage the power-consuming and ecologically hazardous process of flux melting in furnaces. The flux is made by multi-stage crushing of the slag crust, magnetic separation, semifinished product screening and drying.

AN-60SM flux to DIN 32522–81 is of FMS 168 ACM SHP 53-403-40(2-16) class. Slag base is SiO_2–MnO–CaO–CaF_2. Basicity (by IIW formula) is 0.85. Bulk density is 1.3–1.8 kg/dm^3. The metal of weld produced with this flux (St3 + Sv-08A) has the following mechanical properties: yield point – 375 MPa, ultimate tensile strength – 500 MPa. Impact toughness *KCU* at +20 °C is equal to 125 J/cm^2, *KCV* at –20 °C is equal to 40 J/cm^2 (steel 10Kh–SND + Sv-10GN).

Application. Utilisation of flux wastes from welding fabrication allows reducing the purchased quantities of initial flux. AN-60SM flux made from the slag crust is suitable for welding instead of general-purpose fluxes AN-348 A, OSTs-45, ANTs-1 in shipbuilding, tank construction, general and chemical engineering.

Technical and economic advantages. AN-60SM flux ensures 1.5–2 times higher resistance of weld metal to porosity than AN-348A type fluxes (diffusible hydrogen content below 3 cm^3/100 g of weld metal).

Introduction of the technology of slag crust processing allows saving up to 50 % of the initial flux cost due to reuse of regenerated flux in production.

Technology of flux production based on slag crust recycling does not require power-consuming furnace melting of flux accompanied by harmful evolutions into the atmosphere.

State of development. This technology was introduced in Novomoskovsk and Khartsysk pipe plants. AN-60SM flux was introduced in welding parts in Kremenchug Wheel Plant, Kyiv Shipbuilding-Shiprepair Plant, Makeevka Plant of Metal Structures, Snezhnyansk «Khimmash» Plant, etc. Ukrainian specification for AN-60SM flux has been developed.