PECULIARITIES OF TEMPERATURE DISTRIBUTION IN THIN-SHEET ALUMINIUM ALLOY AMg5M IN FRICTION STIR WELDING

A.G. POKLYATSKY
E.O. Paton Electric Welding Institute, NASU, Kiev, Ukraine

Influence of backing material, speed of welding and diameter of tool shoulder on the change in nature of temperature distribution in welded joint cross-section was studied. It was established that formation of permanent joints in friction stir welding takes place at the temperature of not higher than 450 °C.

Keywords: *friction stir welding, aluminium alloy AMg5M, thin sheet, butt joints, thermal cycle, distribution of temperatures*

During friction stir welding (FSW) the processes of deformation and moving along the complex path of material heated till plastic condition, mechanical refining of its components, recrystallisation of grains, diffusion of particles and intensive migration of dislocations, which results in formation of a permanent joint in a solid phase without melting of the base material. The efficiency of proceeding of these processes depends greatly on heat evolution in the places of contact of friction working surfaces of a tool with a metal being welded.

The distribution of temperature fields in the zone of a joint is considerably influenced by thermal physical characteristics of alloys to be welded and parameters of welding process. However, the analysis of results of experimental investigations and theoretic calculations, given in the foreign sources, show that in most cases in welding of aluminium alloys of medium thicknesses the formation of permanent joints takes place at maximal heating temperature of metal of not higher than 500 °C, which amounts about 70–80 % of melting temperature of these materials [1–5]. The metal in welding zone remains at increased temperature for a very short time, which considerably decreases its level of softening and physical-mechanical characteristics as compared to those in fusion welding [6–9].

During welding of thin-sheet semi-products the certain peculiarities arise predetermined by change in nature of heat removal both into backing, on which the formation of a permanent joint takes place, and also in longitudinal and transverse direction of a base material. Moreover, during rotary-onward movement of a working tool in the zones of contact of its working surfaces with the alloy being welded different thermodeformational conditions arise both on the advancing side of a tool (where directions of vectors of its rotary and linear movement coincide), as well as on the its retreating side (where they are moving in opposite directions).

The aim of this work is to investigate the peculiarities of distribution of temperatures in FS-welded butt joints of thin-sheet aluminium alloy AMg5M.

To conduct experimental investigations the aluminium alloy AMg5M widely applied in manufacturing of different welding structures was used. The FSW of sheets 2.8 mm thick was performed in the laboratory installation designed at the E.O. Paton Electric Welding Institute. Special tools with a shoulder of 12 and 14 mm diameter and a conical tip were used for producing butt joints. The rotation speed of tool was 2880 rpm, and the linear speed of its movement along the butt was 8–20 m/h. To compare thermal cycles, AMg5M alloy sheets were automatic TIG-welded in argon by the Fronius installation MW-450 (Austria) at the speed of 10 m/h at 160 A current using welding wire SvAMg5 as a filler material.

The temperature of metal in different zones of welded joints was measured using chromel-alumel thermocouples of 0.1 mm diameter. The results of measurements during welding were registered in the computer using the ICP DAS module of analogue input I-7018P applying EZ Data Logger v431 software. The module was connected to the computer using additional signal converter EX 9530 with the software DCON Utility v5.1.8.

The analysis of obtained results shows that the nature of changes in temperature of material being welded is predetermined by specific conditions of permanent joint formation in solid phase. At the initial stage of FSW process, when rotary tip of tool is gradually deepened into the butt, negligible increase in heat amount evolved as a result of friction occurs (Figure 1). During further deepening of working tool, when contact between end surface of its shoulder and material being welded (at the seventh second) occurs, the heating temperature of the latter begins growing sharply. It occurs unless the tool shoulder penetrates into metal being welded for about 0.1 mm, when between backing and working surfaces of tool the closed space is formed, inside which a plasticized material

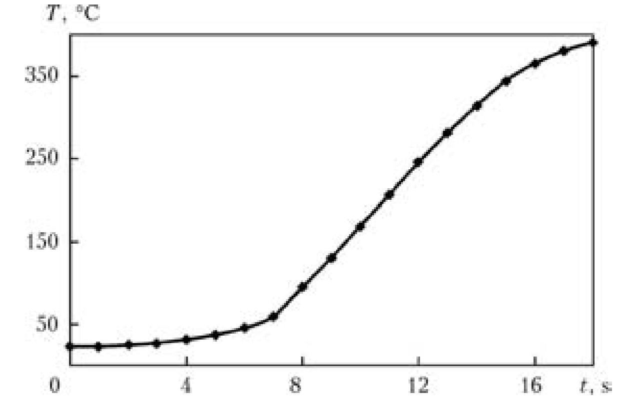

Figure 1. Distribution of temperature of heating of AMg5M alloy at the distance of 6 mm from the weld centre in FSW at v_w = 8 m/h at deepening of working tool with 12 mm diameter shoulder and tip of conical shape

being under high pressure is moving around by the rotary tool and forms a spot weld.

When except of rotary movement the tool starts onward movement along the butt to produce a linear weld, then in front of the advancing side of tool the zone of excessive pressure is formed, from which its working surfaces force out the material heated till plastic condition hindering their movement. This material due to reciprocate movement of tool is constantly moving to the zone releasing behind it. But during movement it forces its way under the high pressure near the tool on its retreating side, where plasticized metal is already present heated up to the same temperature. Obviously when friction appears between these volumes of material, negligible additional heat evolution takes place, which results in 10–15 °C higher temperature of metal in the zone of permanent joint formation always on the retreating side of tool as compared to that on its advancing side (Figure 2).

The heating of material being welded to the maximal temperatures takes place around the tool tip near its base in the zone of abutting the working surface of shoulder. However in welding of thin-sheet materials the tip of tool is very short. Therefore, considerable amount of heat evolved due to friction is spread to the backing where a permanent joint is formed. Consequently, one of the efficient methods to increase temperature of metal in welding zone is the use of backings manufactured of materials with low heat conductivity.

In the course of conducted experimental investigations it was established that when using the asbestos-cement backing instead of steel one in FSW of AMg5M alloy 2.8 mm thick, the temperature of metal near the edge of tool shoulder increases approximately by 20 % at the same condition parameters. Thus, the material being welded is heated up to 450 and 470 °C, respectively, on the advancing and retreating side of tool.

The measurements of temperatures at a different distance from the axis of weld on the retreating side of tool allowed establishing the regularities of con-

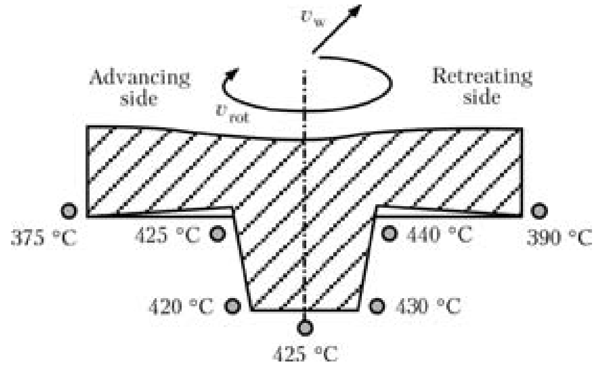

Figure 2. Temperature points of metal in the FS-welded joint on AMg5M alloy at v_w = 8 m/h

duction of a heat field in solid-phase welding of butt joints of thin-sheet aluminium alloys. The obtained results are evidence of the fact in FSW of AMg5M alloy at speed of 8 m/h at 6 mm distance from the axis of weld, the metal is heated up to 390 °C (Figure 3, *a*). The maximal value of the temperature is achieved not at the moment, when the tool is located opposite to the thermocouple, but after its further movement approximately by 2 mm. At the distance of 11 mm from the weld axis, the maximal temperature of heating of the metal (250 °C) is achieved during displacement of heating source from the thermocouple almost by 7 mm. With increase of distance from the weld axis up to 21 mm, the maximal heating temperature of metal decreases to 160 °C during displacement of heating source by 15 mm from the thermocouple. During further increase of distance from the weld axis

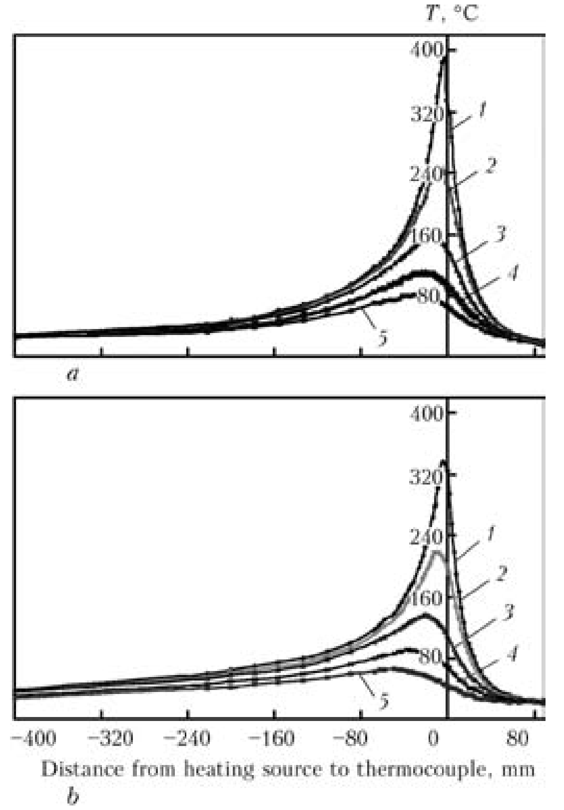

Figure 3. Distribution of temperature in FSW of AMg5M alloy butt joint at v_w = 8 (*a*) and 20 (*b*) m/h and different moving from the weld axis: 6 (*1*), 11 (*2*), 21 (*3*), 31 (*4*) and 40 (*5*) mm

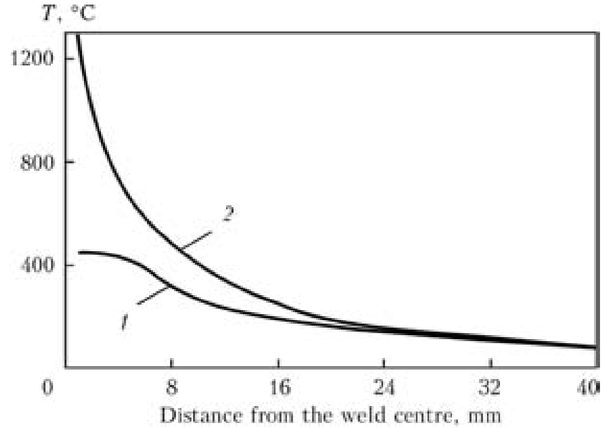

Figure 4. Distribution of temperature in transverse direction of butt joints of AMg5M alloy produced using FSW (*1*) and TIG welding (*2*)

to 31 and 40 mm, the maximal temperature of metal decreases accordingly to 110 and 80 °C. The obtained curves are evidence of rapid heat conduction in transverse and longitudinal directions from the axis of weld in FSW of thin-sheet semi-products of aluminium alloy AMg5M with a high heat conductivity. The segments of the curves corresponding to the processes of heating and cooling of metal bear a non-symmetric character. Thus, thermocouple located near the edge of shoulder shows that, if the tool is at the distance of 5 mm before it, then the metal in this zone is heated approximately to 270 °C and after displacement of the tool to the same distance beyond the thermocouple, the temperature of metal remains at the level of 380 °C, i.e. cooling of metal after welding is slower than its heating. However, the total time of metal being in the process of welding at the temperature higher than 200 °C does not exceed 15 s.

The increase of speed of linear movement of the tool along the butt sufficiently influences the temperature of heating of metal in the zone of welding. Thus, the increase of welding speed from 8 to 20 m/h leads to decrease of temperature of AMg5M alloy near the edge of shoulder on the retreating side of tool from 390 to 350 °C (Figure 3, *b*). Here, the maximal value of temperature of metal in that point is achieved at moving of tool from the thermocouple longer than

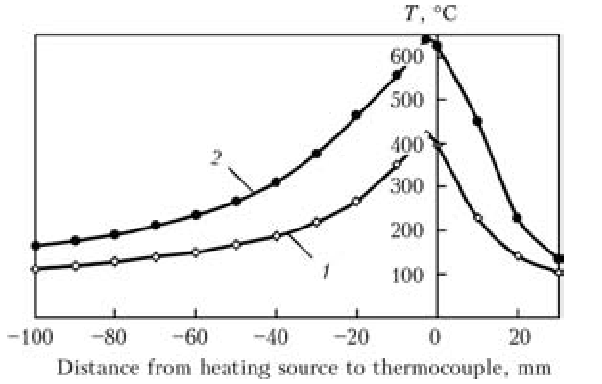

Figure 5. Distribution of temperature in longitudinal direction at the distance of 5 mm from the weld axis in FSW (*1*) and TIG welding (*2*) of butt joints of AMg5M alloy

4 mm. At displacement of the tool beyond the thermocouple almost by 10 mm at the distance from the weld axis of 11 mm, the maximal temperature of metal heating at the welding speed of 20 m/h is about 220 °C. With the increase of distance from the axis of weld to 21, 31 and 40 mm the maximal level of temperature of heating of the metal decreases to 140, 90 and 65 °C, respectively. However, the analysis of produced welded joints showed that at the temperature of heating of AMg5M alloy, which is achieved at welding speed of 20 m/h, the sufficient plasticity of material in the zone of formation of permanent joint is not provided due to which inner defects appear in the welds.

One of the ways to increase the amount of heat evolved in the welding zone is increase of diameter of the tool shoulder [10], that allows increasing the area of its edge surface contacted with a material being welded. In the course of carried out experimental investigations it was established that at the constant speed of welding of 8 m/h the application of the tool with 14 mm diameter shoulder allows increasing the temperature of heating of the metal at the base of tip on the retreating side of tool up to 470 °C. The proportional increase of temperature of metal is observed also in the rest characteristic zones around the working surfaces of tool. Thus, at 14 mm diameter of shoulder near its edge on the retreating side of tool, the metal is heated to 410 °C, which is 20 °C higher than that near the edge of shoulder of 12 mm diameter. The increase of temperature of metal in the zone of permanent joint formation leads to negligible decrease of its cooling rate and increase of time of its stay at increased temperatures.

The comparative analysis of temperature distribution in transverse (Figure 4) and longitudinal (Figure 5) directions of butt joints of AMg5M alloy is the evidence of existing distinction of level of the metal heating in TIG welding and FSW. In TIG welding in the zone of permanent joint formation the complete melting of material takes place. At the distance of 2 mm from the weld axis, the temperature of metal remains at the level of 1000 °C, and near the fusion zone of weld with the base metal at the distance of about 5 mm from the weld axis it approaches to 638 °C, i.e. to the temperature, at which solidification of AMg5M alloy only begins. Besides, heating of metal up to high temperatures during fusion welding predetermines also a wider HAZ. Thus, until the temperatures higher than 200 °C the metal being welded is heated at the distance of 19 mm from the weld axis, while during solid-phase FSW the maximal temperature of heating of metal in the zone of a permanent joint formation does not exceed 450 °C, and at the distance of 5 mm from the weld axis it remains at the level of 410 °C. The heating of metal to the temperatures higher than 200 °C occurs only at the distance of 14 mm from the weld axis.

In the process of cooling of metal at removal of heating source from the place of welding, the gradual decrease of its temperature occurs. Therefore, in TIG welding the metal in the zone of fusion of weld with the base material has the temperature by 150 °C higher than that in FSW even during movement of heating source from this place by 30 mm. And if during solid-phase FSW the temperature of metal at the distance of 5 mm from the weld axis decreases to less than 200 °C at the removal of heating source by 35 mm, then in fusion TIG welding it is decreased at removal by 75 mm. Consequently, maximal temperature of metal heating in the zone of permanent joint formation and total time of stay of base material being welded at high temperatures are reduced, that results in decrease of probability of proceeding the irrevocable physical-chemical processes leading to significant deterioration of mechanical properties of welded joints and causing their deformation.

In conclusion it should be noted that qualitaty formation of welds in FSW of butt joints of aluminium alloy AMg5M 2.8 mm thick is provided at heating of metal in the zone of welding up to 450 °C, which amounts 79 % of temperature of beginning of its melting. Here, at the distance of 5 mm from the weld axis the metal is heated only to the temperature of 410 °C, while in TIG welding still it remains in molten state at 638 °C, i.e. at the temperature of solidification beginning. The decrease of maximal temperature of heating of the zone of welding and reduction of time of stay of material being welded at increased temperatures will have a positive effect on properties of welded joints produced using FSW.

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