of power consumption. For this purpose, the inductor should be placed so that the inductor horizontal axis of symmetry coincided with the upper surface of molten metal in the crucible with a rounded bottom, rising of liquid metal should be prevented at the expense of application of limiting cover and inductor of length not less than its diameter should be used.

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STUDYING THE FEATURES OF MASS TRANSFER IN THE PROCESS OF FRICTION STIR WELDING USING PHYSICAL MODELLING

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Model of the process of friction stir welding was used to study the influence of structural dimensions of working surfaces of tool shoulder and tip on the features of material displacement in the thermodynamic impact zone. It is shown that a permanent joint forms due to displacement of a certain amount of ductile material by the tool tip and its mixing across the entire thickness of edges. Shape of working surface of tool shoulder end face predetermines the displacement trajectory, movement speed, uniformity of mixing and degree of compaction of the materials being joined at solidification.

Keywords: *friction stir welding, process modelling, mass transfer, tool tip design, shoulder working surface*

Permanent joints began to be produced in the solid phase by friction stir welding (FSW) for fabrication of welded structures already in 1990s. This welding process became widely accepted in joining aluminium and magnesium based alloys, which feature a high ductility under the conditions of low-temperature heating [1–4].

Weld formation at FSW takes place at metal heating in the welding zone at the expense of friction to plastic condition and displacement at high pressure in a volume limited by working surfaces of the tool and substrate. FSW main parameters are design features and dimensions of tool working surfaces, its location relative to vertical axis and surfaces of billets being welded, tool pressing and depth of penetration of its tip into the butt, as well as speed of rotation ω and linear displacement of the tool at a certain speed, equal to welding speed v_w [5, 6]. These parameters determine the conditions of metal friction heating in the welding zone and essentially influence the magnitude and orientation of forces acting on plasticized metal, as well as the speed and trajectory of its displacement. Understanding of the features of mass transfer in the zone of permanent joint formation is very important for determination of optimum structural dimensions of the tool and welding process parameters, which will ensure production of dense sound welds.

First idea of the nature of plasticized metal displacement at FSW was obtained through experiments, which are based on instant stopping of the moving material flow [7]. The trajectory of its motion in the characteristic zones of the joint was assessed by the change of the position of special markers (very fine steel balls, copper pins, copper or titanium foil, thin tungsten wire, composite material interlayer, etc.), which were placed in the butt between the edges being welded or on the sections adjacent to it [7–10]. Data on the features of metal displacement can be also obtained in welding aluminium alloys of different alloying systems with different etching to each other [11], or of dissimilar materials differing greatly by their colour [12]. However, all the above methods to assess the mass transfer occurring at FSW are quite labour consuming, as their application requires testing of the produced welded joints by X-ray radiation or prepa-

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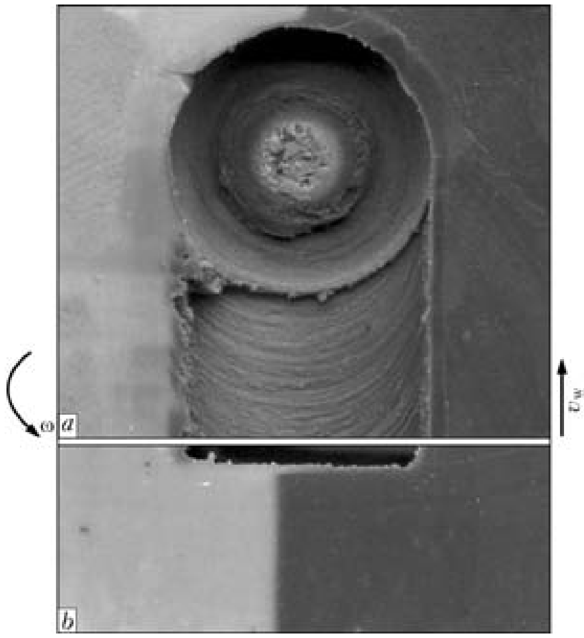

Figure 1. Appearance of face surface (*a*) and transverse section (*b*) of the joint obtained by FSW using a tool without a tip

ration of sections cut out of them by polishing and etching. With this purpose it was proposed to model the FSW process, using plasticin bars of different colours as materials being joined. Sections of such joints in different planes, obtained using tightened steel wire of 0.15 mm diameter, allow without any additional preparation tracing the displacement of materials being joined in the zone of impact of the tool working surface on them.

Such a model allows, in particular, assessment of the influence of structural dimensions of the tool working surfaces on the features of mass transfer during FSW.

Plasticin bars of different colours were butt-joined by linear welds in PWI developed machine for welding sheet aluminium alloys, and then the appearance and sections of the produced joints were studied. Results showed that when the tool is used without the penetrating tip no weld formation occurs across the entire thickness of edges being welded (Figure 1). The weld forms only directly under the shoulder end face at mixing of a very thin metal layer as a result of the tool rotation and displacement along the butt.

The shape of the working surface of tool shoulder end face practically does not influence the weld depth, but has an essential influence on the conditions of mixing of materials, coming from the tool advancing side, where the directions of its rotation and displace-

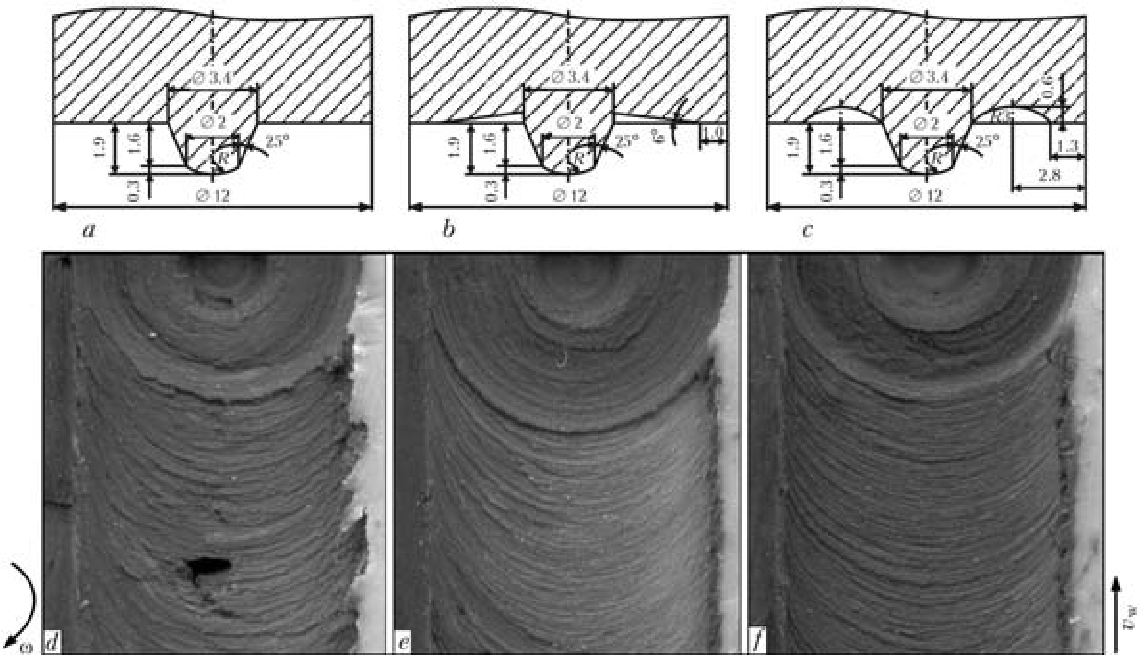

Figure 2. Schematics of working part of tools for FSW with a flat end face surface of the shoulder (*a*), conical (*b*) and semi-spherical (*c*) groove on it and appearance of face surface of welds made using the appropriate tools (*d*–*f*)

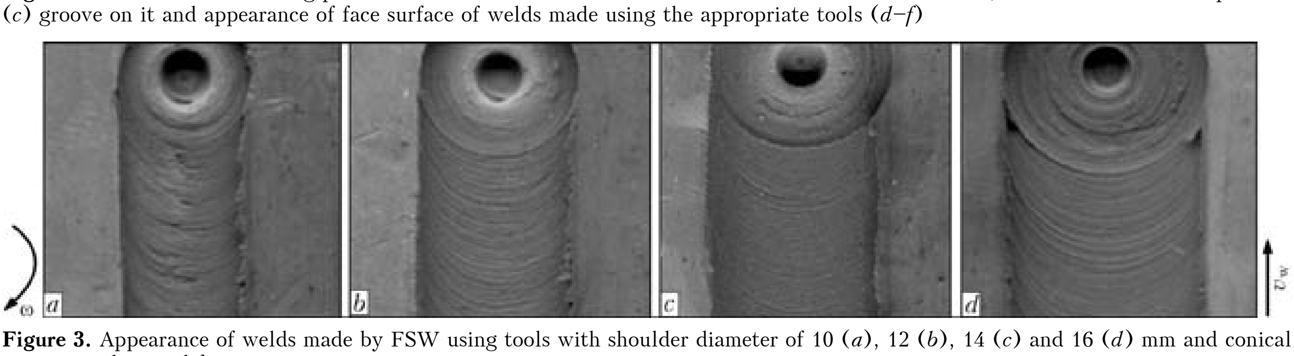

Figure 3. Appearance of welds made by FSW using tools with shoulder diameter of 10 (*a*), 12 (*b*), 14 (*c*) and 16 (*d*) mm and conical groove on their end face

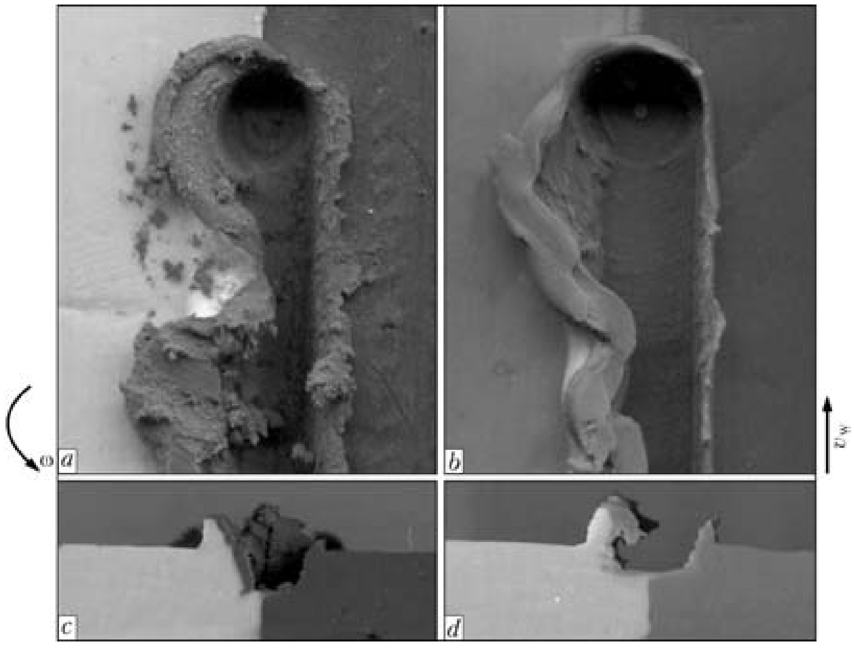

Figure 4. Appearance of face surfaces (a, b) and transverse sections of welds (c, d) produced by FSW without pressing the tool shoulder to materials being joined when using tips of conical shape with a smooth side surface (a, c) and of cylindrical shape with threaded side surface (b, d)

ment coincide (Figure 2, *d*–*f*, *left*) and retreating side, where the directions of its rotation are opposite (Figure 2, *f*–*e*, *right*). Moreover, it predetermines the displacement speed and movement trajectory of mixed portions of materials being joined in a certain limited space, as well as the degree of their compaction at solidification, thus influencing the quality of formation of weld face surface. So, application of tools of different configuration of the shoulder working surface edge can lead to a change on the weld surface of the shape of flakes, frequency of their appearance and distribution by location depth, smoothness of transition from the depressions to protrusions, etc.

Investigation results showed that in welding by a tool with a flat end face of the shoulder a periodical disturbance of the material flow continuity occurs that results in formation of coarse ripple on weld face surface, and of individual tears in some places that impair the joint quality. Presence of a conical or semi-spherical groove on the weld surface promotes a uniform continuous displacement of material and formation of a weld with a practically smooth surface consisting of fine ripple, differing only slightly in thickness. Here, the degree of mixing of materials being welded on the weld face essentially depends on the tool shoulder diameter. Its increase from 10 to 16 mm leads to a considerable increase of the degree of refinement, the weld face becoming more uniform (Figure 3).

In addition to heating material in the welding zone, the tool tip should chiefly ensure its displacement and mixing across the entire thickness of the butt. In order to follow the trajectory of material movement during welding, the shoulder working surface was not pressed to the material being welded directly during displacement of the tool rotating tip along the butt. In Figure 4 it is readily seen that the material was transported by the tip from the tool advancing side (weld right side) to its retreating side (weld left side). A thin layer formed on it, which was located across the entire thickness of tip penetration. Here, the configuration of the tool tip side surface practically did not influence the nature of material displacement. Also visible under the tip end face is a thin interlayer deposited from material located from the tool advancing side.

However, such a displacement of material is only found in the case, if it occurs in an open space, and not in a limited volume. As during FSW the shoulder end face limits material displacement in the vertical direction, the latter is transferred by the tip from the tool advancing side to its retreating side, and then

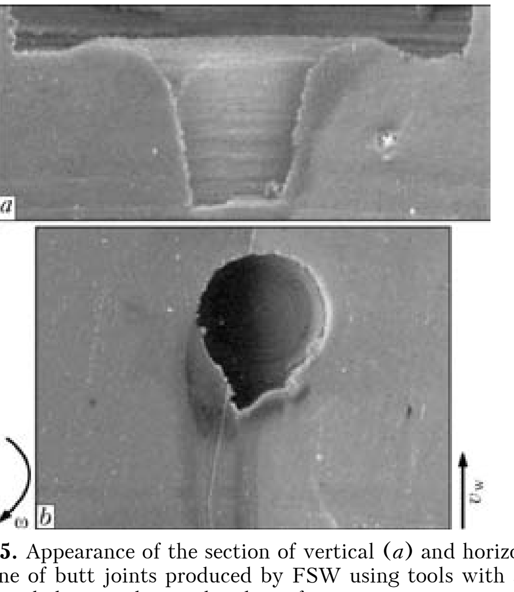

Figure 5. Appearance of the section of vertical (a) and horizontal (b) plane of butt joints produced by FSW using tools with a tip of a conical shape and smooth side surface

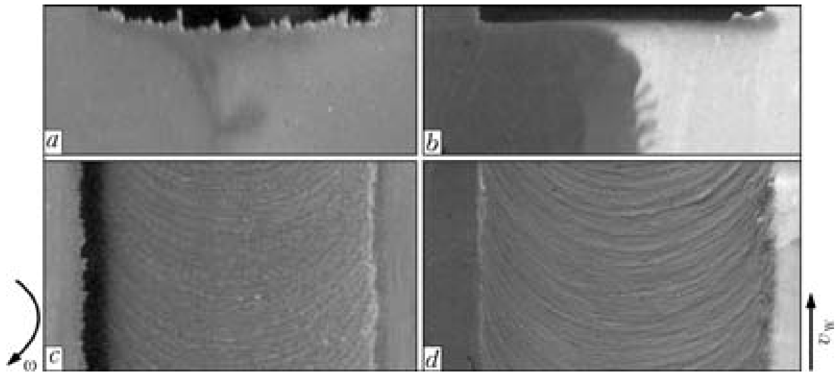

Figure 6. Appearance of cross-sections (a, b) and face surfaces (c, d) of welds produced by FSW using a tool with a tip having smooth side surface (a, c) and thread (b, d)

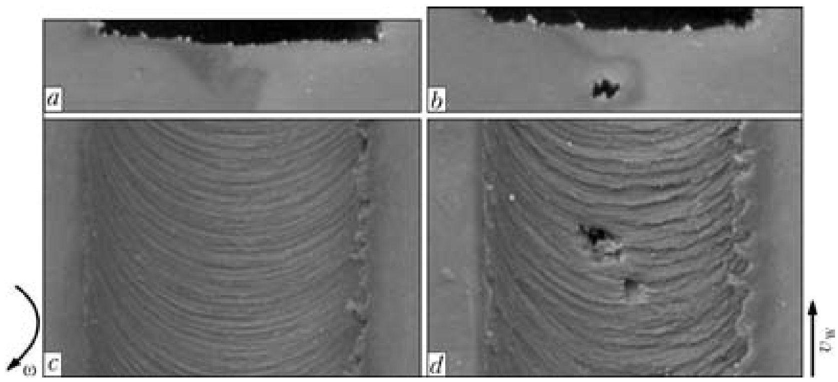

Figure 7. Appearance of cross-sections (a, b) and face surfaces (c, d) of welds produced by FSW using tools with smooth side surface of the tip in the form of a truncated cone of the length of 2.9 (a, c) and 3.2 (b, d) mm

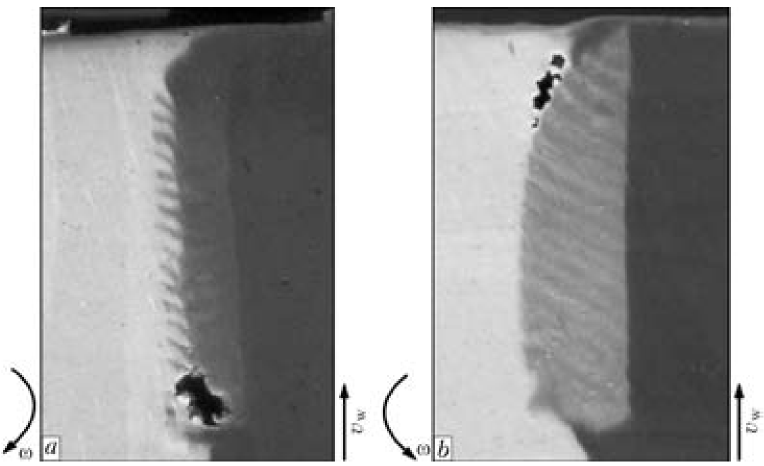

Figure 8. Appearance of cross-sections of welds with characteristic defects formed as a result of insufficient pressing of the shoulder to surfaces being welded at rotation of a tool with tips of a cylindrical shape having cuts in the form of metric thread in the clockwise (a) and counterclockwise (b) direction

into the space freed behind the tip, and is located along the weld axis (Figure 5).

At displacement by the tip of portions of one material located from the tool advancing side to the second material which is located from the tool retreating side, their partial mixing occurs in a closed space at excess pressure. This process can be intensified when using tips with a ramified and not smooth side surface. Using a tip with a standard thread on its side surface, formation of a laminated structure of the weld from the tool retreating side in the zone of its fusion with base material is ensured (Figure 6). However, the nature of formation and appearance of weld face do not essentially depend on the geometry of the tool tip side surface.

Influence of geometrical dimensions and shape, and particularly threads and branching on the tool tip side surface is enhanced at increase of thickness of material being welded. Conducted investigations showed that application of the tool with a smooth side surface of the tip in the form of a truncated cone allows producing sound welds at FSW of materials of about 3 mm thickness (Figure 7). In FSW of even highly ductile materials a defect in the form of a cavity quite often forms in the central part of the butt closer to weld root. Stability of formation of weld face part here also deteriorates with tears forming on it, and this results in insufficient compaction of material over the shoulder working surface. There is no smooth transition between the layers forming on the butt surface, which differ significantly both by thickness and by height that is indicative of periodical violation of continuity of the flow of materials being joined.

Presence of threads or ramification on the tool tip side surface can have an essential influence on the process of weld formation as a result of the change of direction and trajectory of material displacement in the joint zone. Here, certainly orientation of thread on the tool tip is interrelated with the direction of the tool rotation. Use of one and the same tool with a tip of a cylindrical shape, having cuts in the form of metric thread, can lead to formation of defects in different sections of the weld in case of insufficient pressing of the shoulder to the surfaces being welded (Figure 8). At tool rotation the material, present in the butt zone, is displaced by the thread from its lower part into the upper part, thus leading to formation of discontinuities in the weld root. At the change of direction of tool rotation the material moves along the thread on the tool tip side surface in-depth of the butt, that results in formation of a tight weld in its root part, and appearance of a cavity near the shoulder end face.

CONCLUSIONS

1. Studying the features of mass transfer in the zone of thermodynamic action at modeling the FSW process allowed establishing that formation of a permanent joint occurs as a result of transfer of a certain volume of ductile material by the tool tip from the edge being welded from the tool advancing side to plasticized material located on the opposite edge, their mixing and displacement under pressure in the space that is freed behind the tip at its movement along the butt.

2. Structural features of tool tips determine the trajectory of ductile material movement in the zone of permanent joint formation. To ensure sound formation of welds at increase of joined edge thickness above 3 mm, it is rational to apply tools with tips having a ramified side surface that ensures intensive mixing of materials across the entire thickness of the butt.

3. Configuration of working surface of tool shoulder influences the nature of mixing of materials being joined only on the weld face, and determines the degree of ductile material compaction behind the tool tip. Presence of a conical or semi-spherical groove on the shoulder working surface promotes a uniform continuous displacement of ductile material and formation of a practically smooth weld surface with ripple of almost the same thickness, the presence of which is indicative of alternation of joined material layers.

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