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PREDICTION OF PARAMETERS OF FRICTION STIR WELDING PROCESS OF SHEET ALUMINIUM ALLOYS

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Optimum parameters of the modes of friction stir welding of 0.8–3.0 mm thick aluminium alloys widely used in fabrication of welded structures were determined. It is shown that sound formation of welds can be ensured at tool immersion into the metal being welded to the depth of 0.10–0.15 mm due to correct selection of the frequency of tool rotation and welding speed. A relationship is established between the total content of alloying and modifying elements in the aluminium alloy being welded, welding speed and frequency of tool rotation. A range of optimum relationships was determined, showing the length of the tool linear movement along the butt during one rotation, when sound formation of welds of sheet aluminium alloys AMtsN, AD33, AMg2M, 1460, AMg5M, 1201 and AMg6M is provided. Formulas were derived, which express the dependencies in the form of power functions, limiting this range and allowing calculation of the required speeds of tool rotation and displacement for any aluminium alloy, containing 2.2–8.4 % of alloying and modifying elements. Characteristic defects, forming in welds at deviation of the above parameters from the optimum range, are shown. 18 Ref., 5 Figures.

Keywords: *aluminium alloys, friction stir welding, tool rotation speed, welding speed, characteristic defects*

Friction stir welding (FSW), being one of the novel methods for obtaining permanent joints in solid phase, finds wider and wider application in shipbuilding, manufacture of land and air transport, space engineering, etc. [1–4].

Formation of a weld as a result of heating due to friction to plastic state, stirring and plastic deformation of small volume of metal of parts being joined in closed space, provides some advantages of this process in comparison with fusion welding. First of all it allows eliminating the possibility of defect formation in form of hot cracks, pores, macroinclusions of oxide film and such, provoked by melting and crystallization of metal. Besides, welding of aluminium alloys is carried out without application of shielding gas and filler material and allows eliminating ultraviolet radiation, metal fumes and vapors emission. This guarantees high mechanical properties of joints and decrease of level of base metal softening and deformation of welded structures [3, 5–8].

However, as with any method of welding, obtaining of defect-free joints in FSW is possible only at specific parameters of the process. Incorrect selection or their deviation from the optimum values can result in formation of characteristic surface or inner defects in form of flash, lack of fusion or discontinuities [9–11].

It is believed that the main parameters of FSW process, except for structural peculiarities of working surfaces of a tool, are angle of tool tilt relatively to vertical axis, pressing force of tool to the surfaces of parts being joined, value of immersion of tool shoulder and depth of penetration of tool pin into welded metal as well as rotation speed and its linear displacement (welding speed) [5, 9].

The investigations carried by foreign specialists showed that welding shall be carried out with «forward angle», deviating the tool at small angle from vertical axis. At that due to force applied to the tool in vertical plane its shoulder insignificantly immerses into metal being welded and is tightly pressed against it in process of welding. Tip of the tool should provide stirring of metal along the whole thickness of edges being welded in order to eliminate a defect in form of lack of fusion in low part of weld [12–15]. Speeds of rotation and linear displacement of the tool to significant extent determine the volume of plasticized metal in a welding zone and temperature of its heating. They can change in sufficiently wide range depending on thickness of material being welded, its thermal and physical and ductile characteristics as well as trajectory of displacement of plasticized metal determined by structural peculiarities of tool working surfaces [9, 16]. Some researchers determined the optimum relationships between the welding speeds and tool rotation frequencies, expressing length of linear displacement of the tool along the butt per its one revolution, depending on thickness of material being welded or temperature interval of crystallization of aluminium alloys [14, 17].

Aim of the present work is to determine the optimum parameters of modes of friction stir welding widely used in manufacture of welded structures of aluminium alloys of different alloying systems of 0.8–3.0 mm thickness.

Investigation procedure. Friction stir welding of sheets of aluminium alloys AMtsN, AD33, AMg2M, AMg5M, AMg6M, 1201 and 1460 of thickness from 0.8 to 3.0 mm was carried out on a laboratory unit, designed at the E.O. Paton Electric Welding Institute. A special tool with 12 mm diameter shoulder and pin of conical shape [18] was used to obtain butt joints. Length of tool pin was selected in such a way as it was 0.15 mm smaller than the thickness of metal being welded. It was forward angle welding at 2–3° tool tilt relatively to vertical axis. Tool rotation was carried out using replaceable serial asynchronous alternating current motors (U = 380 V) of 4 kW power and shaft rotation frequency N = 1420 and 2880 rpm set on a support. Using the latter the tool fixed on the motor shaft moved in a vertical plane thanks to which necessary immersion of its working parts into the material being welded was provided and value of axial force of its pressing to the parts being joined in process of welding was kept. The sheets being welded were safely fixed on a steel substrate of movable table. At that speed of welding can be varied in v_w = 2–42 m/h limits. Specially set ahead of the tool pressure roll prevented a change in the process of welding of spatial position of edges of thin-sheet material, which is too sensitive to heat effect.

Presence of macrodefects in form of flash and lack of fusion on the surfaces of welded joints was determined using visual inspection. The inner defects were found on cross-sections, preliminary prepared using electrolytic polishing and their additional etching in a solution of perchloric, nitric and hydrofluoric acids, using optical microscope MIM-8M.

Investigation results and their discussion. As a result of carried investigations it was determined that quality formation of welds in friction stir welding of sheet aluminium alloys can be provided by correct selection of depth of tool immersion into metal being welded, frequency of tool rotation and speed of its linear displacement along the butt or welding speed (v_w).

Depth of tool immersion provokes thermodeformational conditions in all zones of welded joint, since simultaneously predetermines a value of tool shoulder immersion and depth of pin penetration into metal being welded. Its reduction (< 0.10 mm) results in decrease of value of shoulder immersion and depth of penetration of tool pin into metal being welded. As a result, pressure under the shoulder working surface and tool pin and value of heat emission in the place of their contact with metal being welded are reduced. Due to this, the necessary volume of plasticized metal for quality weld formation is not provided or required level of its plasticization is not reached in the zone of formation of permanent joint. This can lead to formation of inner defects in form of discontinuities (Figure 1, *a*) or surface defects from weld face in form of lack of fusion (Figure 1, *b*). Besides, as a result of

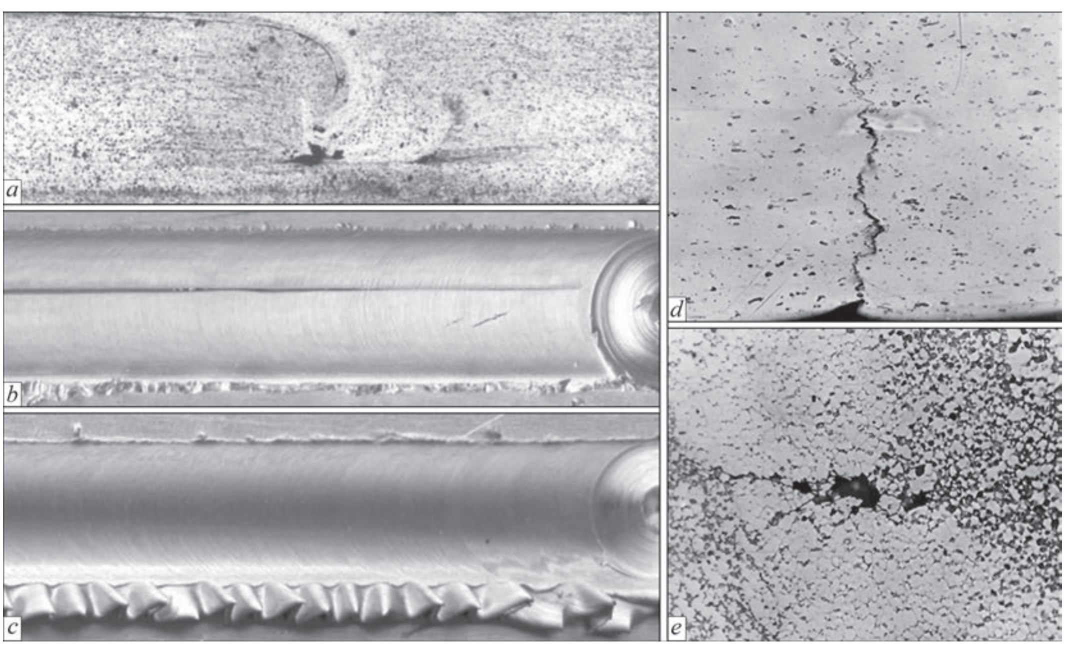

Figure 1. Characteristic defects forming in FSW welds: *a*, *e* — inner discontinuities; *b* — lack of fusion from weld face; *c* — flash on weld face; *d* — lack of fusion in weld root part (*a* — ×15; *b*, *c* — ×2; *d* — ×300; *e* — ×500)

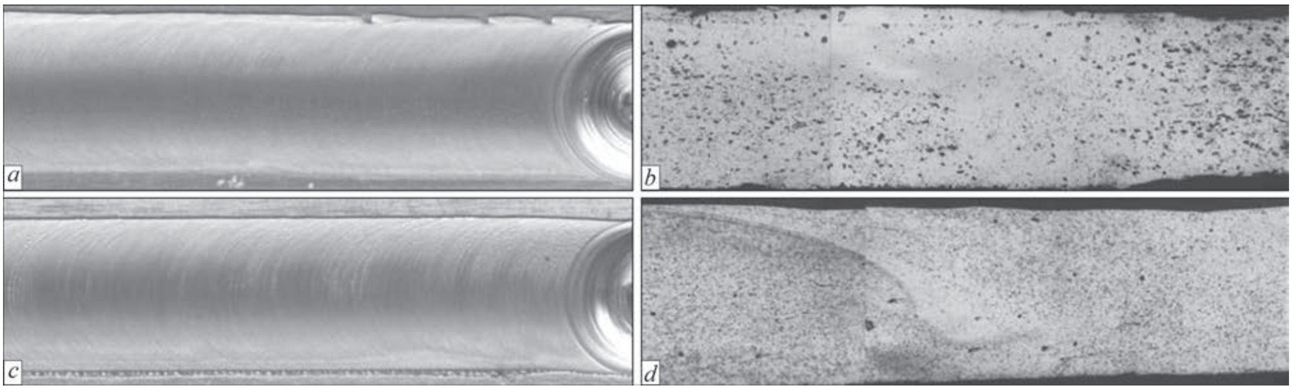

Figure 2. Appearance (*a*, *c* — ×2) and transverse macrosections (*b*, *d* — ×12) of FSW welds of aluminium alloys AMtsN (*a*, *b*) and AMg2M (*c*, *d*) of 2 mm thickness produced at welding speeds 38 and 32 m/h, respectively

decrease of tool penetration depth into the metal being welded and emitted in its friction heat, the defects in form of lack of fusion (Figure 1, *d*) can also appear in the root part of the weld. Quality of welded joints can be deteriorated by excessive (> 0.15 mm) deepening of the tool. Thus, welding of ductile low aluminium alloys (AMtsN, AD33, AMg2M) can provoke formation of surface defects in form of flash (Figure 1, *c*) on the weld face, and in welding of stronger alloys these are inner discontinuities, caused by metal overheating (Figure 1, *e*). Therefore, in order to provide quality formation of welds it is necessary to immerse the tool into metal being welded to 0.10–0.15 mm depth and keep it in such position in process of welding due to axial pressing force.

Conditions of plastic deformation of metal in the zone of formation of permanent joint are determined by temperature of its heating and deformation rate, which depend on frequency of tool rotation and rate of its linear displacement along the butt. Carried experimental investigations proved that quality formation of welds in friction stir welding of different aluminium alloys is provided at different values of these parameters. Thus, at frequency of tool rotation $N = 1420$ rpm ductile low aluminium alloys are successfully welded at sufficiently high welding speeds (Figure 2).

To obtain quality joints on stronger aluminium alloys containing significant amount of alloying and modifying elements it is necessary to reduce welding speed. For example, in the welds of aluminium-lithium alloy 1460 the inner defects in form of cavities, provoked by insufficient volume of plasticized metal in a zone of permanent joint formation, are formed in tool displacement along the weld with more than

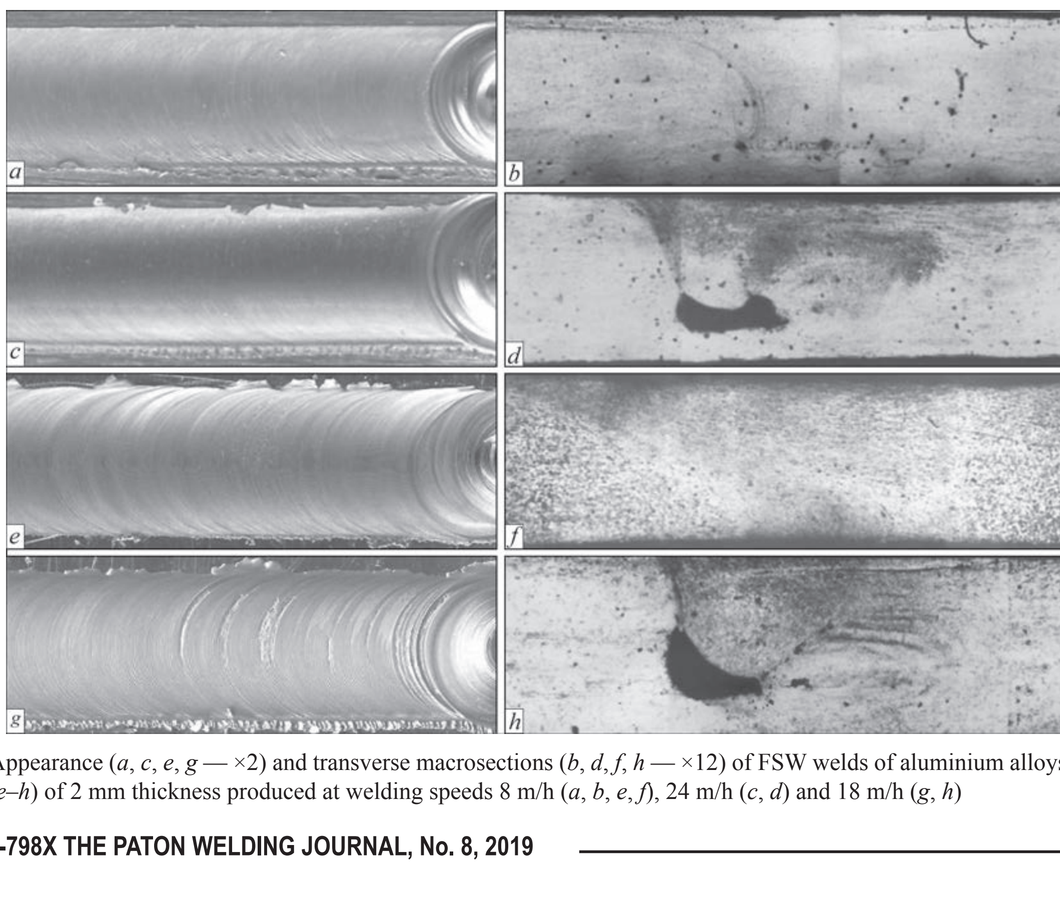

Figure 3. Appearance (*a*, *c*, *e*, *g* — ×2) and transverse macrosections (*b*, *d*, *f*, *h* — ×12) of FSW welds of aluminium alloys 1460 (*a*–*d*) and 1201 (*e*–*h*) of 2 mm thickness produced at welding speeds 8 m/h (*a*, *b*, *e*, *f*), 24 m/h (*c*, *d*) and 18 m/h (*g*, *h*)

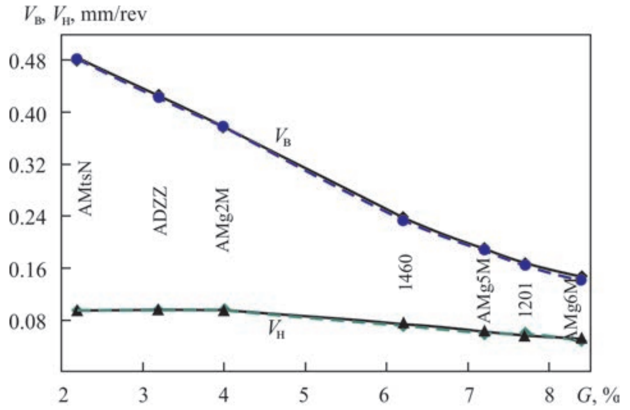

Figure 4. Range of optimum relationships of welding speeds and tool rotation frequencies in FSW of aluminium alloys with different content of alloying and modifying elements and approximated curves limiting it (N = 1420–2880 rpm)

20 m/h speed, and in 1201 alloy welds it makes more than 14 m/h (Figure 3).

Increase of tool rotation frequency to 2880 rpm provokes rise of heat emission in a zone of permanent joint formation that allows 2 times increase of speed of linear displacement of a tool without deterioration of welds' quality. Taking into account relationship between noted parameters of the process, v_w/N relationship was used. It expresses length of linear displacement of the tool along butt per its one revolution. Carried experimental investigations allowed determining the optimum values of this relationship depending on total content of alloying and modifying elements in welded aluminium alloys (Figure 4).

It is determined that in friction stir welding of aluminium alloy AMtsN, containing around 2.2 % of alloying and modifying elements, quality formation of the welds is provided at value of v_w/N relationship in 0.094–0.481 mm/rev limits, i.e. at tool rotation frequency 1420 rpm the welding speed can vary in 8–41 m/h limits. For alloy AD33, in which content of such elements makes around 3.2 %, the range of optimum v_w/N relationships reduces to 0.094–0.423 mm/rev, that at mentioned above frequency of tool rotation allows successfully performing welding on 8–36 m/h speed. Quality formation of welds based on AMg2M alloy, containing higher amount of alloying and modifying elements (4 %) is reached at value of v_w/N relationship in 0.094–0.376 mm/rev limits or at v_w = = 8–32 m/h.

For stronger aluminium alloys, containing considerable amount of alloying and modifying elements, the range of optimum v_w/N relationships, which provide quality weld formation, becomes significantly narrower. Thus, for alloy 1460, which in its content has around 6.2 % of other elements in addition to aluminium, it makes 0.070–0.233 mm/rev, i.e. at tool rotation frequency 1420 rpm the welding speed should be in 6–20 m/h limits and at 2880 rpm it is 12–40 m/h. On alloy AMg5M, containing 7.2 % of alloying and modifying elements, quality formation of welds is provided at v_w/N = 0.058–0.187 mm/rev or at welding speeds 5–16 and 10–32 m/h, when the tool rotation frequency makes 1420 and 2880 rpm, respectively. More doped alloy 1201, containing 7.7 % of other elements in addition to aluminium, is successfully welded at value of linear displacement of the tool per its one revolution in 0.047–0.163 mm limits, that corresponds to 5–14 m/h welding speeds at tool rotation frequency 1420 rpm and 10–28 m/h at 2880 rpm. For alloy AMg6M, containing around 8.4 % of alloying and modifying elements, the optimum v_w/N relationship is in 0.047–0.140 mm/rev range, i.e. welding speed can vary in 4–12 m/h limits at tool rotation frequency 1420 rpm or 8–24 m/h at 2880 rpm.

Obtained empirical curves, limiting the range of optimum relationships between the length of linear displacement of tool per its one revolution and total content of alloying and modifying elements in the alloy, were approximated by power functions. For the curve, limiting upper boundary of this range such a function will be expressed by the following formula:

$$V_B(G) = V_{B0}[1.46–0.08G/G_0 – – 0.541(G/G_0)^2 + 0.16(G/G_0)^3], \quad (1)$$

where $V_B(G)$ is the maximum allowable value of linear displacement of the tool per its one revolution, which provides quality formation of welds, mm/rev; V_{B0} = 0.376 mm/rev is the maximum allowable value of linear displacement of tool per its one revolution for alloy AMg2M; G_0 = 4 % is the total content of alloying and modifying elements in aluminium alloy AMg2M; G is the total content of alloying and modifying elements in welded aluminium alloy, % (2.2–8.4 % range).

For the curve, limiting lower boundary of indicated range, the approximated dependence can be expressed by such formula:

$$V_H(G) = V_{H0}[0.64 + 1.12G/G_0 – – 0.972(G/G_0)^2 + 0.197(G/G_0)^3], \quad (2)$$

where $V_H(G)$ is the minimum allowable value of linear displacement of the tool per its one revolution, which provides quality formation of welds, mm/rev; V_{H0} = 0.094 mm/rev is the minimum allowable value of linear displacement of the tool per its one revolution for alloy AMg2M.

The curves presented on the diagram (see Figure 4) by solid lines, obtained using approximated formula dependencies virtually match with dashed curves plotted based on the results of experimental investigations. Therefore, in friction stir welding of aluminium alloys containing total amount of alloying and modifying elements within 2.2–8.4 % limits the range of optimum relationships between the speeds of linear displacements and tool rotation frequency, which provide quality weld formation, can be determined using formulae given above.

Increase or decrease of the set optimum v_w/N relationships for aluminium alloys containing specific amount of alloying and modifying elements results in formation of defects in the welds. Exceeding the set maximum allowable speed of tool displacement per its one revolution by 10–20 % leads to appearance in the welds of inner discontinuities (see Figure 1, *a*) caused by insufficient plasticization of metal in the welding zone. Its further increase provokes formation of surface defects in form of lacks of fusion (see Figure 1, *b*) from the weld face.

Decrease of v_w/N relationship below the set minimum allowable value in welding of ductile aluminium alloys with small content of alloying and modifying elements (AMtsN, AD33, AMg2M) results in formation of defects in form of flash (see Figure 1, *c*) from the weld face. In welding of the rest of alloys decrease of minimum allowable speed of tool displacement per its one revolution by 10–20 % provokes appearance of areas of overheated metal on weld face (Figure 5). And its further reduction promotes in the welds formation of inner discontinuities caused by metal overheating (see Figure 1, *e*).

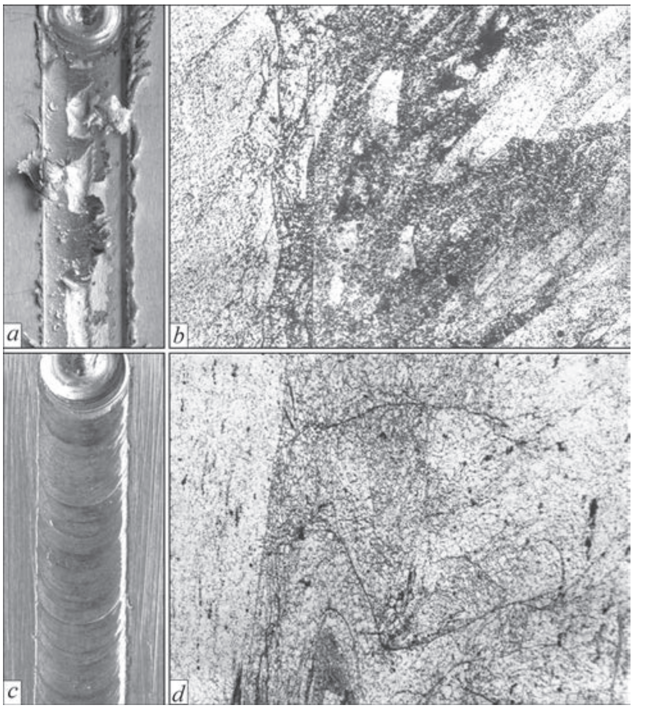

Figure 5. Appearance (*a*, *c* — ×2) and microstructure (*b*, *d* — ×125) of face of FSW welds of 1420 alloy of 1.8 mm thickness; *a*, *b* — overheated weld; *c*, *d* — normal

Conclusions

1. Quality weld formation in friction stir welding of sheet (0.8–3.0 mm) aluminium alloys of different doping systems can be provided at tool immersion into metal being welded by 0.10–0.15 mm depth due to proper selection of tool rotation frequency and welding speed.

2. Ductile low aluminium alloys are successfully welded at sufficiently high welding speeds. At N = = 1420 rpm tool rotation frequency the speed of its linear displacement for alloy AMtsN can vary in 8–41 m/h limits, for AD33 alloy it is 8–36 m/h and for AMg2M alloy — 8–32 m/h. Welding speed shall be reduced to obtain quality joints on stronger aluminium alloys containing significant amount of alloying and modifying elements.

3. Range of the optimum relationships of welding speeds and tool rotation frequencies in friction stir welding of aluminium alloys depends of total content in them of alloying and modifying elements. At 2.2 % of their total content in alloy (AMtsN alloy) the value of tool linear displacement per its one revolution can change in sufficiently wide limits from 0.094 to 0.423 mm. For stronger high alloys the range of its change narrows to 0.047–0.163 mm at 7.7 % content (1201 alloy) of such elements in alloy being welded and to 0.047–0.140 mm at their content of 8.4 % (AMg6M alloy). Deviation of indicated parameters from the optimum range results in formation of typical inner and surface defects, caused by insufficient plasticization or overheating of material being welded.

4. The curves limiting the range of optimum relationships of welding speeds and tool rotation frequencies, plotted based on the results of experimental investigations and approximated by formula dependencies in form of power functions, allow calculation of necessary rotation and displacement speeds of tool for any aluminium alloy containing 2.2–8.4 % of alloying and modifying elements.

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