doi: 10.18323/2782-4039-2024-2-68-4

Influence of tool geometry on the formation of welded joint during friction stir welding of the AA5083 aluminum alloy

Igor N. Zybin*[1], PhD (Engineering), Associate Professor,
assistant professor of Chair "Technologies of Connection and Processing of Materials"
Darya A. Buzyreva, graduate student
Kaluga Branch of Bauman Moscow State Technical University, Kaluga (Russia)

***E-mail:** igor.zybin@bmstu.ru,
igor.zybin@mail.ru

[1]ORCID: https://orcid.org/0000-0002-5738-4231

Received 18.10.2023 *Accepted 08.02.2024*

Abstract: One of the important parameters influencing the formation of a weld during friction stir welding is the tool geometry, which affects the processes of heat generation and stirring of metals in their connection zone. These processes influence the formation of a high quality and strength welded joint without continuity defects. In this regard, it is relevant to analyze the influence of tool geometry on the welding mode parameters, at which the welded joint is formed without continuity defects, as well as on the welded joint strength under static tension. The work considers the influence of the cylindrical and conical shapes of the tool pin, as well as the conical shape of the pin with a thread on its outer surface and a spiral groove on the end surface of the tool shoulder on the welding mode parameters, at which the welded joint is formed without continuity defects. The study shows that changing the shape of the pin working surface from cylindrical to a conical one had no effect on the range of welding mode parameters, at which the welded joint is formed without continuity defects. It has been found that the presence of a thread on the pin outer surface and a groove on the end surface of a tool shoulder allows producing welded joints without continuity defects in a wider range of welding mode parameters compared to a simpler tool geometry. The macrostructure of the resulting welded joints was considered. It has been found that the studied tool geometry has almost no influence on the maximum strength values of welded joints produced by friction stir welding and reaches 95 % of the strength of the base metal.

Keywords: friction stir welding; AA5083; tool geometry; strength of the welded joint without continuity defects.

For citation: Zybin I.N., Buzyreva D.A. Influence of tool geometry on the formation of welded joint during friction stir welding of the AA5083 aluminum alloy. *Frontier Materials & Technologies*, 2024, no. 2, pp. 43–52. DOI: 10.18323/2782-4039-2024-2-68-4.

INTRODUCTION

One of the modern advanced methods of joining metals is friction stir welding (FSW). Welding is performed without melting the materials being joined, which means the absence of defects in the joint that are characteristic of arc welding methods. High strength of the welded joint – up to 90–95 % of the base metal strength is ensured [1; 2], and the resulting welded joints are characterized by minimal deformations.

It is known that the tool geometry has a significant influence on the processes of plastic deformation and stirring of the metal, the formation of the structure, the processes of heat release in the welding zone, and the mechanical properties of the welded joint [3–5]. It plays an important role in the formation of a high-quality welded joint without defects.

Currently, tool geometry is characterized by a wide variety [6–8]. The tool consists of two main elements: a pin and a shoulder; both are involved in the process of stirring the metal [3], and have a strong influence on the flow of metal during the welding process [9].

The tool pin is mainly responsible for the direction of the plasticized material flow during welding, the trajectory of which is quite complex [10]. The geometric shape of the tool pin has a significant impact on the processes of heat release in the metal joining zone, and the amount of heat, in turn, affects the structure of a weld, the width of the heat-affected zone, and the quality of a welded joint. In addition, the shape of the tool pin affects the strength of a weld [11]. The pin, in most cases, has a cylindrical or conical surface. When using a pin with a conical surface, the cone angle, as a rule, does not exceed 20°, which is associated with a decrease in tensile strength and elongation at large angles. The pin conical surface may have grooves, threads, and other elements, controlling the plasticized material flow. The use of a conical pin with a thread ensures better stirring of the metal [12; 13]. Stirring the metal several times, before its deposition, helps to remove pores and destroy oxides.

It has been found that the presence of a thread on a pin causes a slight increase in temperature, near the pin, and enhances the flow and mixing of metal [14]. The pin diameter, as a rule, is comparable to the thickness of the samples to be connected, and its length is tenths of a millimeter less than the thickness of the metal. The end of a pin is usually flat or spherical. The former is easier to manufacture, while the latter provides less tool wear.

The shape of the tool shoulder can be flat, concave or convex. The shoulder end surface can be smooth or with notches, grooves and other elements. The presence of various projections on the tool shoulder surface, such as a spiral groove, contributes to better stirring of the metal. The tool shoulder, along with the pin, provides the necessary heat generation in the zone of its friction with the parts to be welded. Moreover, it provides compaction of the metal and its forging during the welding process.

When selecting tool sizes, it is important to choose the ratio of the shoulder diameter to the tool pin diameter. This ratio plays an important role in the heat release as well as in the stirring of the metal during welding. According to works [15; 16], it is recommended to choose this ratio around 3:1. In this case, better grain refinement and high joint strength are ensured.

In the work [17], using the example of welded joints made of AA5083 aluminum alloy it is shown that the rolling direction influences the strength characteristics of the resulting welded joint. It is necessary to consider this fact when producing welded joints by FSW.

One of the important parameters of welding is the productivity of the process, which can be raised by increasing the welding speed. However, it is not always possible to increase the welding speed, and hereby to ensure a welded joint without continuity defects in the joint zone. Therefore, it is necessary to know whether increasing the complexity of the tool geometry allows expanding the range of parameters of the welding mode, which ensures the production of a welded joint without continuity defects, and whether it is possible to increase the welding speed. Note that during FSW, the welding speed and tool rotation frequency are interrelated. As a rule, when increasing the welding speed, it is necessary to adjust the tool rotation speed. These parameters directly affect the heat release processes in the metal joining zone. Insufficient or excessive heat generation in the welding zone can lead to defects.

In the literature, there is a significant number of works studying the influence of tool geometry on the production of a welded joint from the AA5083 aluminum alloy. In most cases, minor changes in process parameters (typically tool rotation speed and welding speed) are considered for this material. The depth of tool penetration into the sample is often assumed as a constant value, although it has a significant impact on the process of forming a welded joint. Therefore, it is of interest to study the influence of different tool geometry shapes on the welding mode parameters, at different depths of tool penetration into the sample.

The purpose of this work is to study the influence of tool geometry on the welding mode parameters, ensuring the absence of continuity defects in the metal joining zone, and on the strength of the welded joint under static tension.

METHODS

To carry out experimental studies on FSW, sheets of AA5083 aluminum alloy with a thickness of 5 mm were used, butt welding was performed. Tool geometric parameters: pin diameter at the base was 6.5 mm, shoulder diameter was 18.5 mm, and pin length was 4.75 mm. The pin end surface was rounded. The cone angle of the pin surface was 20°. The tool was made of H13 alloy steel, GOST 5950-2000, and hardened at a temperature of 1020 °C, and then tempered at a temperature of 500 °C. The hardness of the working surface of the tool was 53...57 HRC.

Three types of instruments were used during the study (Fig. 1).

Welding was performed on a FSS-400R vertical milling machine (Belarus), the spindle of which has the ability to rotate relative to the vertical axis at an angle of ±45°. The angle of tool inclination to the vertical was constant and amounted to 2°. The rotation frequency and welding speed were changed discretely. Welding of the samples was carried out on a substrate in the form of a Steel 20 sheet, with a thickness of 10 mm. The rolling direction for all samples was the same, and was chosen perpendicular to the weld. The edges of the surfaces to be joined were milled and degreased with acetone before welding. The welding mode parameters (Table 1) were considered in a wide range and were selected taking into account the capabilities of the equipment used at different values of tool shoulder penetration into the sample. The depth of shoulder penetration into the sample was in the range of 0.05...0.4 mm.

a ***b*** ***c***

Fig. 1. *Geometry of a tool for friction stir welding:*
a *– tool with a cylindrical shape of the pin;* ***b*** *– tool with a conical shape of the pin;*
c *– tool with a conical shape of the pin with a thread and a groove on the end surface of the tool shoulder*
Рис. 1. *Геометрические формы инструмента для СТП:*
a *– инструмент с цилиндрической формой пина;* ***b*** *– инструмент с конической формой пина;*
c *– инструмент с конической формой пина с резьбой и канавкой на торцевой поверхности заплечика*

Static tensile tests of welded samples were carried out on an IR 5092-100 universal tensile testing machine (Russia). The dimensions of the samples are shown in Fig. 2. At least three samples were prepared for testing in the same mode. Fig. 3 shows the examples of samples for static tensile tests.

RESULTS

After conducting experimental studies in the selected range of welding mode parameters, the appearance of the welded joints was examined, and macrosections of the cross sections of the welded samples were made to identify possible continuity defects.

Analysis of macrosections showed that when welding samples with tools with cylindrical and conical pin surfaces (Fig. 1 a, 1 b), a welded joint without continuity defects was produced under the following welding modes: tool rotation speed 450–560 rpm, welding speed 31.5–50 mm/min, depth of tool shoulder penetration into the sample 0.05–0.4 mm. One should note that at a tool rotation speed of 710 rpm, a welding speed of 50 mm/min, and a depth of tool shoulder penetration into the part from 0.1...0.15 to 0.4 mm, welded joints without defects in

Table 1. *Values of welding mode parameters for AA5083 aluminum alloy*
Таблица 1. *Значения параметров режимов сварки алюминиевого сплава АМг5*

Tool rotation frequency, rpm	Welding speed, mm/min	Tool angle of inclination to the vertical, °	Depth of tool shoulder penetration into the sample, mm
450–1400	31.5–120.0	2	0.05–0.40

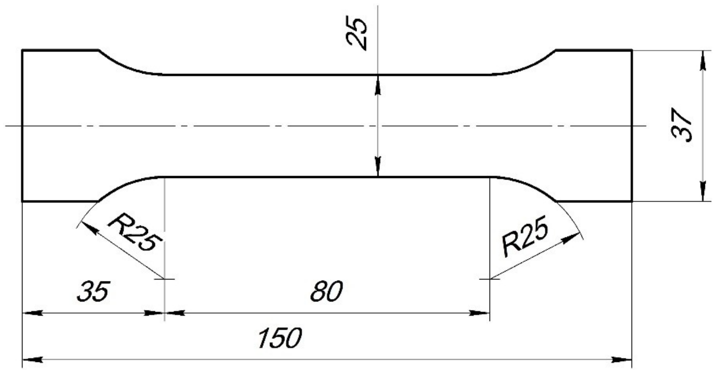


Fig. 2. *Geometrical dimensions of the specimen for static tensile tests*
Рис. 2. *Геометрические размеры образца для испытаний на статическое растяжение*

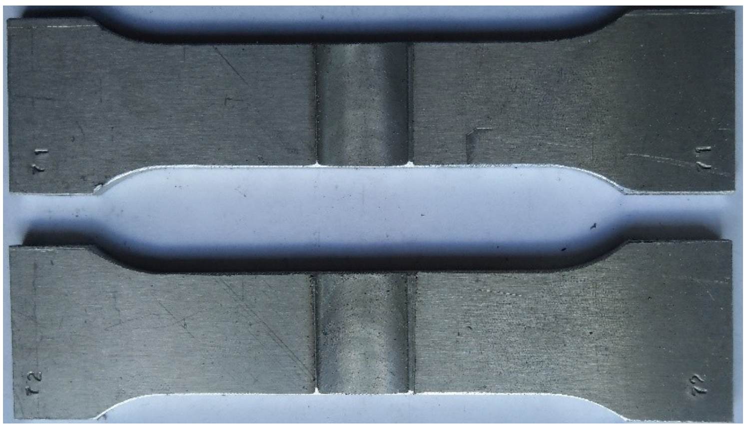


Fig. 3. *Specimens for static tensile tests*
Рис. 3. *Образцы для проведения испытаний на статическое растяжение*

the joint zone were also obtained. When the depth of tool shoulder penetration into the part was up to 0.1...0.15 mm, the lack of fusion was usually observed in the weld root. At a depth of more than 0.4 mm, significant burr was observed at the periphery of the welded joint, due to the extrusion of a large volume of metal into this zone. Examples of the appearance and macrosections of welded joints produced with tools with cylindrical and conical pin surfaces in different welding modes are shown in Fig. 4, 5.

Analysis of macrosections obtained by welding samples using a tool with a conical pin surface (Fig. 1 c), which has a thread on the outer surface and a spiral groove on the shoulder end surface, showed that a welded joint without continuity defects was produced under the following welding modes: rotation speed tool is 450–1120 rpm, welding speed is 31.5–125 mm/min. Fig. 6, 7 show the examples of the appearance and macrosections of welded joints produced using different welding modes.

The values of the ranges of mode parameters (tool rotation frequency and welding speed) for all considered tools are given in Fig. 8.

It was not possible to produce a welded joint without continuity defects outside zones 1 and 2 shown in Fig. 8. The types of main defects in welded joints produced during FSW are given in Fig. 9.

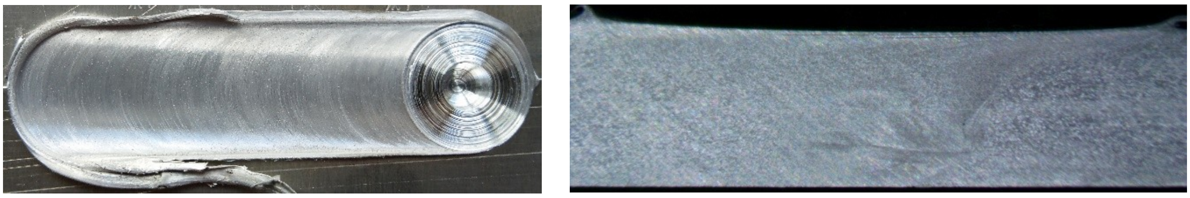
When using tools with a smooth pin surface (Fig. 1 a, 1 b), there was no onion ring structure on macrosections of cross sections of welded joints (Fig. 4 b, 5 b). When using a tool with a thread on the pin outer surface (Fig. 1 c), an onion ring structure was visible on macrosections (Fig. 6 b, 7 b).

When carrying out static tensile tests on welded samples without continuity defects produced using different tool shapes, the ultimate stress values shown in Table 2 were obtained. The table presents the ultimate stress values, indicating the ranges of welding modes.

According to experimental data, the static tension strength of the base metal was 327.1 MPa (average value). The rolling direction in these samples coincided with the tensile force direction during static tension tests.

DISCUSSION

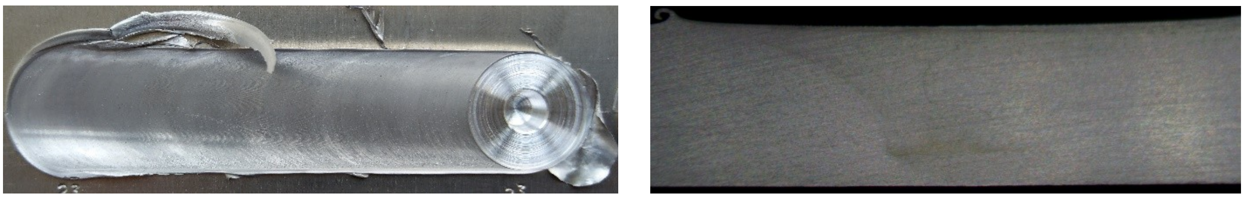
Analysis of the results showed that in the case of all studied shapes of the tool working surface, welded joints without continuity defects were obtained.



a ***b***

Fig. 4. *Appearance (**a**) and macrosection (**b**) of the cross section of the welded joint produced by a tool with a cylindrical pin shape (Fig. 1 a). Welding mode parameters: tool rotation frequency is 560 rpm, welding speed is 50 mm/min, and the depth of tool shoulder penetration into the sample is 0.07 mm*

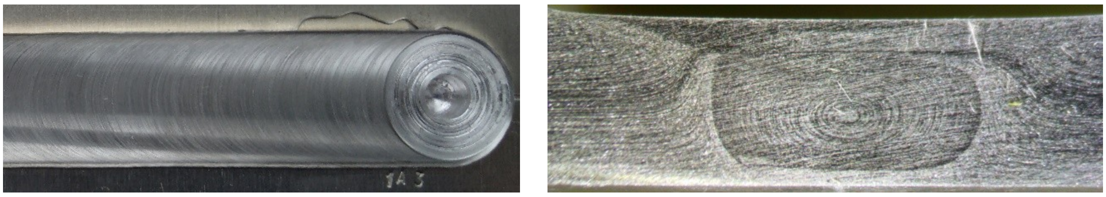
Рис. 4. *Внешний вид (**a**) и макрошлиф (**b**) поперечного сечения сварного соединения, полученного инструментом с цилиндрической формой пина (рис. 1 a). Параметры режимов сварки: частота вращения инструмента 560 об/мин, скорость сварки 50 мм/мин, глубина внедрения заплечика инструмента в образец 0,07 мм*



a ***b***

Fig. 5. *Appearance (**a**) and macrosection (**b**) of the cross section of the welded joint produced by a tool with a conical pin shape (Fig. 1 b). Welding mode parameters: tool rotation frequency is 450 rpm, welding speed is 31.5 mm/min, and the depth of tool shoulder penetration into the sample is 0.05 mm*

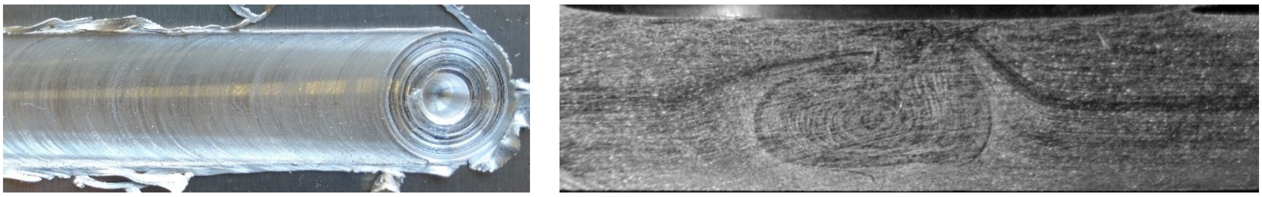
Рис. 5. *Внешний вид (**a**) и макрошлиф (**b**) поперечного сечения сварного соединения, полученного инструментом с конической формой пина (рис. 1 b). Параметры режимов сварки: частота вращения инструмента 450 об/мин, скорость сварки 31,5 мм/мин, глубина внедрения заплечика инструмента в образец 0,05 мм*



a *b*

Fig. 6. *Appearance (**a**) and macrosection (**b**) of the cross section of the welded joint produced by a tool with a conical pin shape with a thread and a spiral groove on the end surface of the tool shoulder (Fig. 1 c). Welding mode parameters: tool rotation frequency is 710 rpm, welding speed is 50 mm/min, and the depth of tool shoulder penetration into the sample is 0.06 mm*

Рис. 6. *Внешний вид (**a**) и макрошлиф (**b**) поперечного сечения сварного соединения, полученного инструментом с конической формой пина с резьбой и спиральной канавкой на торцевой поверхности заплечика инструмента (рис. 1 c). Параметры режимов сварки: частота вращения инструмента 710 об/мин, скорость сварки 50 мм/мин, глубина внедрения заплечика инструмента в образец 0,06 мм*



a *b*

Fig. 7. *Appearance (**a**) and macrosection (**b**) of the cross section of the welded joint produced by a tool with a conical pin shape with a thread and a spiral groove on the end surface of the tool shoulder (Fig. 1 c). Welding mode parameters: tool rotation frequency is 1120 rpm, welding speed is 125 mm/min, and the depth of tool shoulder penetration into the sample is 0.07 mm*

Рис. 7. *Внешний вид (**a**) и макрошлиф (**b**) поперечного сечения сварного соединения, полученного инструментом с конической формой пина с резьбой и спиральной канавкой на торцевой поверхности заплечика инструмента (рис. 1 c). Параметры режимов сварки: частота вращения инструмента 1120 об/мин, скорость сварки 125 мм/мин, глубина внедрения заплечика инструмента в образец 0,07 мм*

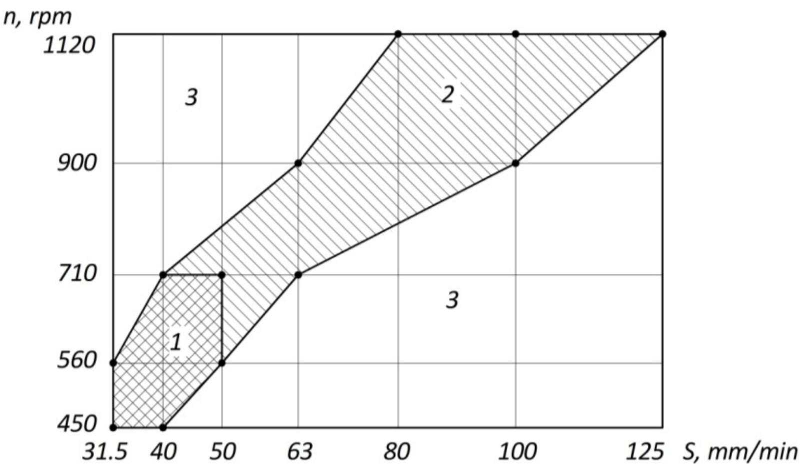
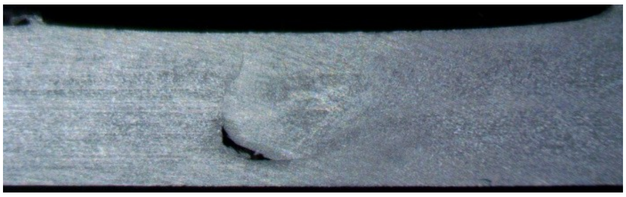


Fig. 8. *Rotation frequency (n) and welding speed (s) when producing butt joints by friction stir welding:*
1 – zone without continuity defects (cylindrical and conical shapes of the tool pin without a thread);
2 – zone without continuity defects (conical shape of the pin with a thread and a spiral groove on the end surface of the tool shoulder), including zone 1;
3 – zone with continuity defects (for all tool types)

Рис. 8. *Частота вращения (n) и скорость сварки (s) при получении стыковых соединений СТП:*
1 – зона отсутствия дефектов сплошности (цилиндрическая и коническая форма пина инструмента без резьбы);
2 – зона отсутствия дефектов сплошности (коническая форма пина с резьбой и спиральной канавкой на торцевой поверхности заплечика инструмента), включающая в себя зону 1;
3 – зона наличия дефектов сплошности (для всех типов инструментов)



a ***b***

Fig. 9. *Main types of defects of welded joints produced by friction stir welding:*
a *– faulty root fusion;* ***b*** *– lack of fusion*
Рис. 9. *Основные виды дефектов сварных соединений, полученных при СТП:*
a *– непровар в корне сварного шва;* ***b*** *– несплавление*

Table 2. *Welding mode parameters and ultimate stress limits of welded joints, which ensured the production of a welded joint without continuity defects*
Таблица 2. *Параметры режимов сварки и пределы прочности сварных соединений, при которых обеспечивалось получение сварного соединения без дефектов сплошности*

Welding mode parameters			**Ultimate stress range, (average value), MPa**
Tool rotation frequency, rpm	**Welding speed, mm/min**	**Depth of tool shoulder penetration into the sample, mm**	
Tool with a cylindrical pin shape (Fig. 1 a)			
450–560	31.5–50.0	0.05–0.40	304,3–318,8 (310,4)
710	50.0	(>0.10…0.15)–0.40	
Tool with a conical pin shape (Fig. 1 b)			
450–560	31.5–50.0	0.05–0.40	308.5–313.6 (311.5)
710	50.0	(>0.10…0.15)–0.40	
Tool with a conical pin shape with a thread and a spiral groove on the end surface of the tool shoulder (Fig. 1 c)			
450–1120	31.5–125.0	0.05–0.40	306.0–313.4 (309.7)

In the works of other authors, there is no information on changing the ranges of welding mode parameters (tool rotation frequency and welding speed) for the production of defect-free welded joints, including the values of these parameters when using a tool without a thread on the pin, as well as with a thread on the pin and a spiral groove at the tool shoulder end surface.

It is found that for cylindrical and conical pin shapes, the ranges of rotational speed and welding speed, at which a welded joint without continuity defects is ensured, coincide. The influence of replacing a cylindrical pin shape with a conical one on the parameters of welding modes for producing defect-free welded joints was not identified in this work.

The thread on the pin outer surface, and the spiral groove on the tool shoulder end surface (Fig. 1 c) significantly improve the conditions for forming a welded joint, which allowed producing welded joints without continuity defects in a wider range of welding mode parameters (rotation frequency and welding speed), compared to a simpler geometry tool (Fig. 1 a, 1 b). By increasing the welding speed, the process productivity can be increased.

Faulty root fusion (Fig. 9 a), as a rule, is characteristic of a low number of revolutions and high welding speed, which leads to insufficient mixing and plasticization of the metal, and heat supply to the welding zone. Lack of fusion (Fig. 9 b) was often observed at a large number of revolutions and different welding speeds, which is likely caused by the excessive heat generation in the metal joining zone.

The presence of an onion structure in welded joints produced by a tool with a pin, having a thread on the outer surface and a spiral groove on the shoulder end surface, is explained by the fact that layers of metal are extruded along the threaded groove of the pin with each revolution of the tool. The onion ring shape caused by different distribution of grain sizes along the spiral [18] is typical when using a tool with a pin having a thread on the surface to produce welded joints from aluminum alloys, including the AA5083 alloy [19]. When using a tool with a smooth pin outer surface, the metal is stirred in the welding zone constantly and monotonously, and not intermittently. The presence of an onion structure characterizes better conditions for the formation of a weld, which allows using the higher welding speeds to produce welded joints without continuity defects.

The thread on the pin surface contributes to greater grain refinement in the welded joint area. According to the Hall–Petch equation, a decrease in grain size leads to an increase in tensile strength [20]. The experimental studies carried out in the work showed that the maximum values of the ultimate strength obtained for all considered tool geometry forms, are close to each other and amount to about 95 % of the strength of the base metal, i. e., the tool geometry did not affect the maximum values of the ultimate strength.

It was found that when using a cylindrical pin shape and a depth of tool shoulder penetration into the sample not exceeding 0.1...0.15 mm, the maximum value of the tensile strength reached 213.6 MPa (65 % of the strength of the base metal). For a conical pin shape with the same shoulder penetration depth, the maximum value of the ultimate strength reached 295.7 MPa (90 % of the strength of the base metal). In the work [21], when producing welded joints from aluminum alloys, including AA5083 aluminum alloy with a thickness of 0.8...3 mm, using a tool with a conical pin without a thread, it is recommended the tool shoulder to be penetrated into the sample to a depth of 0.1...0.15 mm, since at other depths, defects are formed in the weld. In our case, when using a pin with a thread on the outer surface and a spiral groove on the shoulder end surface, the maximum values of the tensile strength did not depend on the depth of tool shoulder penetration into the sample. It should be noted that, as a rule, when the shoulder penetration depth does not exceed 0.1...0.15 mm, subsequent mechanical processing of the welded joint to remove burr is not required.

The above indicates that at small depths of tool shoulder penetration into the sample, its geometry has a special influence on the processes of stirring metals in the welding zone. It is known that the tool shoulder is responsible for stirring the metal in the upper third of the sample thickness, and this stirring is enhanced in the presence of a spiral groove [9]. The presence of such a groove improves stirring due to the involvement of a larger volume of metal, in the process of plastic deformation, and stirring, a larger surface area of contact between the tool and the metal, which leads to a higher temperature in the joint zone, and lower viscosity of the metal. The use of a tool shoulder with a spiral groove on the end surface together with a threaded pin helps to achieve a higher tensile strength compared to the flat form of the shoulder, when penetrated into the sample to a depth of no more than 0.1...0.15 mm.

Studies aimed at analyzing the depth of tool penetration into the sample, which ensures maximum strength of the welded joint, have not been previously carried out for the cases of tool geometry and AA5083 aluminum alloy considered in the work. The results obtained are important in terms of performing welding with minimal amounts of tool shoulder penetration into the sample. In this case, there is no need for subsequent mechanical processing of the weld to remove flash, which reduces the cost of manufacturing welded products.

Experimental studies have shown that with a cylindrical tool without a thread on the pin, it is possible to obtain the strength of the welded joint at the same level as a tool with a thread on the pin, and a groove on the shoulder end surface.

The work [22], when analyzing the influence of the welding mode parameters of the AA5083 aluminum alloy on the defectiveness of the welded joint structure, noted the importance of the heat input coefficient defined as the ratio of the welding speed to the tool rotation frequency, and characterizing the heat introduced into the welding zone. In [23], defect-free welded joints from AA5083 aluminum alloy were produced at a given ratio in the range of 0.05...0.26 mm/rev. The author [21] found that the heat input coefficient when forming AA5083 aluminum alloy welded joints, without continuity defects, corresponded to the range of 0.058...0.187 mm/rev. Analysis of the results of experimental studies carried out in this work showed that the heat input coefficient in zones 1 and 2 (Fig. 8) corresponds to values in the range of 0.056...0.11, which is consistent with the data of [21; 23].

CONCLUSIONS

Changing the shape of the working surface of the tool pin from cylindrical to a conical one, had no effect on the choice of the range of welding mode parameters ensuring the absence of continuity defects, as well as on the static tensile strength.

The presence of a thread on the working surface of the tool pin, and a spiral groove on the shoulder end surface, leads to the formation of a welded joint without continuity defects in a wider range of mode parameters compared to tools without the above elements.

The maximum tensile strength values for joints produced using cylindrical and conical pins without threads, are ensured, when the shoulder penetrates into the sample to a depth of more than 0.1...0.15 mm, and for a conical pin with threads – from 0.05 mm.

For all considered forms of tool geometry, the maximum values of the static tensile strength reached 95 % of the strength of the base metal.

REFERENCES

1. Arbegast W.J. Friction stir welding after a decade of development. *Welding Journal*, 2006, vol. 85, no. 3, pp. 28–35.
2. Okamura H., Aota K., Ezumi M. Friction stir welding of aluminum alloy and application to structure. *Journal of Japan Institute of Light Metals*, 2000, vol. 50, no. 4, pp. 166–172. DOI: 10.2464/jilm.50.166.
3. Manigandan K., Senthilkumar S. Review of friction stir welding tools. *Journal of Advanced Engineering Research*, 2018, vol. 5, no. 1, pp. 41–51.
4. Chandrashekar A., Ajay Kumar B.S., Reddappa H.N. Friction stir welding: tool Material and geometry. *AKGEK International Journal of Technology*, 2015, vol. 6, no. 1, pp. 16–20.

5. Yang Min, Bao Rui-jun, Liu Xiu-zhong, Song Chao-qun. Thermo-mechanical interaction between aluminum alloy and tools with different profiles during friction stir wielding. *Transactions of Nonferrous Metals Society of China*, 2019, vol. 29, no. 3, pp. 495–506. DOI: 10.1016/S1003-6326(19)64958-7.
6. Kumar P.M., Anbumalar V., Ramesh Babu K.R. A review on progress of different types of friction stir welding tool geometry design. *Australian Journal of Basic and Applied Sciences*, 2014, vol. 16, no. 8, pp. 364–371.
7. Ratković N., Jovanović Pešić Ž., Arsić D., Pešić M., Džunić D. Tool geometry effect on material flow and mixture in FSW. *Advanced Technologies & Materials*, 2022, vol. 47, no. 2, pp. 33–36. DOI: 10.24867/ATM-2022-2-006.
8. Zhang Y.N., Cao X., Larose S., Wanjara P. Review of tools for friction stir welding and Processing. *Canadian Metallurgical Quarterly*, 2012, vol. 51, no. 3, pp. 250–261. DOI: 10.1179/1879139512Y.0000000015.
9. Ambrosio D., Morisada Y., Ushioda Y., Fujii H. Material flow in friction stir welding: A review. *Journal of Materials Processing Technology*, 2023, vol. 320, article number 118116. DOI: 10.1016/j.jmatprotec.2023.118116.
10. Kumar R., Pancholi V. Three-dimensional material flow during friction stir welding of AA5083. *Journal of Manufacturing Processes*, 2021, vol. 68-A, pp. 1214–1223. DOI: 10.1016/j.jmapro.2021.06.051.
11. Mohanty H.K., Mahapatra M.M., Kumar P., Biswas P., Mandal N.R. Effect of tool shoulder and pin probe profiles on friction stirred aluminum welds – a comparative study. *Journal of Marine Science and Application*, 2012, vol. 11, pp. 200–207. DOI: 10.1007/s11804-012-1123-4.
12. Meshram S., Madhusudhan Reddy G., Venugopal Rao V. Role of threaded tool pin profile and rotational speed on generation of defect free friction stir AA 2014 aluminium alloy welds. *Defence Science Journal*, 2016, vol. 66, no. 1, pp. 57–63. DOI: 10.14429/dsj.66.8566.
13. Hassan Kh.A.A., Prangnell P.B., Norman A.F., Price D.A., Williams S.W. Effect of welding parameters on nugget zone microstructure and properties in high strength aluminium alloy friction stir welds. *Science and Technology of Welding and Joining*, 2003, vol. 8, no. 4, pp. 257–268. DOI: 10.1179/136217103225005480.
14. Jiang Tao, Wu Chuan Song, Shi Lei. Effects of tool pin thread on temperature field and material mixing in friction stir welding of dissimilar Al/Mg alloys. *Journal of Manufacturing Processes*, 2022, vol. 74, pp. 112–122. DOI: 10.1016/j.jmapro.2021.12.008.
15. Vijayavel P., Balasubramanian V., Sundaram S. Effect of shoulder diameter to pin diameter (D/d) ratio on tensile strength and ductility of friction stir processed LM25AA-5% SiCp metal matrix composites. *Materials and Design*, 2014, vol. 57, pp. 1–9. DOI: 10.1016/j.matdes.2013.12.008.
16. Vijayavel P., Sundararajan T., Rajkumar I., Ananthakumar K. Effect of tool diameter ratio of tapered cylindrical profile pin on wear characteristics of friction stir processing of Al–Si alloy reinforced with SiC ceramic particles. *Metal Powder Report*, 2021, vol. 76, no. 2, pp. 75–89. DOI: 10.1016/j.mprp.2020.04.005.
17. Gusarova A.V., Rubtsov V.E., Kolubaev E.A., Bakshaev V.A., Nikitin Yu.V. The influence of the rolling direction of AA5056 on the microstructure and properties of weld joints obtained by friction stir welding. *Obrabotka metallov / Metal working and material science*, 2020, vol. 22, no. 4, pp. 124–136. DOI: 10.17212/1994-6309-2020-22.4-124-136.
18. Alemdar A.S.A., Jalal S.R., Mulapeer M.M. Effect of exfoliation corrosion on the efficient hybrid joint of AA2024-T3 and AA2198-T8 formed by friction stir welding. *Heliyon*, 2023, vol. 9, no. 6, article number e16577. DOI: 10.1016/j.heliyon.2023.e16577.
19. Sizova O.V., Kolubaev A.V., Kolubaev E.A., Zaikina A.A., Rubtsov V.E. Fracture of friction stir welded butt joints structure of aluminum-magnesium alloy. *Obrabotka metallov / Metal working and material science*, 2014, no. 3, pp. 14–20. EDN: SKXOBD.
20. Dawood H.I., Mohammed K.S., Rahmat A., Uday M.B. Effect of small tool pin profiles on microstructures and mechanical properties of 6061 aluminum alloy by friction stir welding. *Transactions of Nonferrous Metal Society of China*, 2015, vol. 25, no. 9, pp. 2856−2865. DOI: 10.1016/S1003-6326(15)63911-5.
21. Poklyatskiy A.G. Parameters of FSW process of thin sheet aluminium alloys. *Vestnik of Polotsk State University. Part B. Industry. Applied Sciences*, 2015, no. 11, pp. 53–58. EDN: UOHBAH.
22. Sizova O.V., Kolubaev A.V., Kolubaev E.A., Zaikina A.A., Rubtsov V.E. Effect of main parameters of the friction stir welding on structure imperfections of welded joint. *Obrabotka metallov / Metal working and material science*, 2017, no. 4, pp. 19–29. DOI: 10.17212/1994-6309-2017-4-19-29.
23. Ovchinnikov V.V., Drits A.M. Technological peculiarities of friction welding with Al–Mg aluminum alloys stir. *Science intensive technologies in mechanical*, 2019, no. 3, pp. 7–20. DOI: 10.30987/article_5c7434ed5317f2.05345899.

СПИСОК ЛИТЕРАТУРЫ

1. Arbegast W.J. Friction stir welding after a decade of development // Welding Journal. 2006. Vol. 85. № 3. P. 28–35.
2. Okamura H., Aota K., Ezumi M. Friction stir welding of aluminum alloy and application to structure // Journal of Japan Institute of Light Metals. 2000. Vol. 50. № 4. P. 166–172. DOI: 10.2464/jilm.50.166.
3. Manigandan K., Senthilkumar S. Review of friction stir welding tools // Journal of Advanced Engineering Research. 2018. Vol. 5. № 1. P. 41–51.
4. Chandrashekar A., Ajay Kumar B.S., Reddappa H.N. Friction stir welding: tool Material and geometry // AKGEK International Journal of Technology. 2015. Vol. 6. № 1. P. 16–20.
5. Yang Min, Bao Rui-jun, Liu Xiu-zhong, Song Chao-qun. Thermo-mechanical interaction between aluminum alloy and tools with different profiles during friction stir wielding // Transactions of Nonferrous Metals Society of China. 2019. Vol. 29. № 3. P. 495–506. DOI: 10.1016/S1003-6326(19)64958-7.
6. Kumar P.M., Anbumalar V., Ramesh Babu K.R. A review on progress of different types of friction stir welding tool geometry design // Australian Journal of Basic and Applied Sciences. 2014. Vol. 16. № 8. P. 364–371.

7. Ratković N., Jovanović Pešić Ž., Arsić D., Pešić M., Džunić D. Tool geometry effect on material flow and mixture in FSW // Advanced Technologies & Materials. 2022. Vol. 47. № 2. P. 33–36. DOI: 10.24867/ATM-2022-2-006.
8. Zhang Y.N., Cao X., Larose S., Wanjara P. Review of tools for friction stir welding and Processing // Canadian Metallurgical Quarterly. 2012. Vol. 51. № 3. P. 250–261. DOI: 10.1179/1879139512Y.0000000015.
9. Ambrosio D., Morisada Y., Ushioda Y., Fujii H. Material flow in friction stir welding: A review // Journal of Materials Processing Technology. 2023. Vol. 320. Article number 118116. DOI: 10.1016/j.jmatprotec.2023.118116.
10. Kumar R., Pancholi V. Three-dimensional material flow during friction stir welding of AA5083 // Journal of Manufacturing Processes. 2021. Vol. 68-A. P. 1214–1223. DOI: 10.1016/j.jmapro.2021.06.051.
11. Mohanty H.K., Mahapatra M.M., Kumar P., Biswas P., Mandal N.R. Effect of tool shoulder and pin probe profiles on friction stirred aluminum welds – a comparative study // Journal of Marine Science and Application. 2012. Vol. 11. P. 200–207. DOI: 10.1007/s11804-012-1123-4.
12. Meshram S., Madhusudhan Reddy G., Venugopal Rao V. Role of threaded tool pin profile and rotational speed on generation of defect free friction stir AA 2014 aluminium alloy welds // Defence Science Journal. 2016. Vol. 66. № 1. P. 57–63. DOI: 10.14429/dsj.66.8566.
13. Hassan Kh.A.A., Prangnell P.B., Norman A.F., Price D.A., Williams S.W. Effect of welding parameters on nugget zone microstructure and properties in high strength aluminium alloy friction stir welds // Science and Technology of Welding and Joining. 2003. Vol. 8. № 4. P. 257–268. DOI: 10.1179/136217103225005480.
14. Jiang Tao, Wu Chuan Song, Shi Lei. Effects of tool pin thread on temperature field and material mixing in friction stir welding of dissimilar Al/Mg alloys // Journal of Manufacturing Processes. 2022. Vol. 74. P. 112–122. DOI: 10.1016/j.jmapro.2021.12.008.
15. Vijayavel P., Balasubramanian V., Sundaram S. Effect of shoulder diameter to pin diameter (D/d) ratio on tensile strength and ductility of friction stir processed LM25AA-5% SiCp metal matrix composites // Materials and Design. 2014. Vol. 57. P. 1–9. DOI: 10.1016/j.matdes.2013.12.008.
16. Vijayavel P., Sundararajan T., Rajkumar I., Ananthakumar K. Effect of tool diameter ratio of tapered cylindrical profile pin on wear characteristics of friction stir processing of Al–Si alloy reinforced with SiC ceramic particles // Metal Powder Report. 2021. Vol. 76. № 2. P. 75–89. DOI: 10.1016/j.mprp.2020.04.005.
17. Гусарова А.В., Рубцов В.Е., Колубаев Е.А., Бакшаев В.А., Никитин Ю.В. Влияние направления проката АМг5 на микроструктуру и свойства сварных соединений, полученных сваркой трением с перемешиванием // Обработка металлов (технология, оборудование, инструменты). 2020. Т. 22. № 4. С. 124–136. DOI: 10.17212/1994-6309-2020-22.4-124-136.
18. Alemdar A.S.A., Jalal S.R., Mulapeer M.M. Effect of exfoliation corrosion on the efficient hybrid joint of AA2024-T3 and AA2198-T8 formed by friction stir welding // Heliyon. 2023. Vol. 9. № 6. Article number e16577. DOI: 10.1016/j.heliyon.2023.e16577.
19. Сизова О.В., Колубаев А.В., Колубаев Е.А., Заикина А.А., Рубцов В.Е. Разрушение стыковых соединений алюминиево-магниевого сплава, выполненных способом сварки трением с перемешиванием // Обработка металлов (технология, оборудование, инструменты). 2014. № 3. С. 14–20. EDN: SKXOBD.
20. Dawood H.I., Mohammed K.S., Rahmat A., Uday M.B. Effect of small tool pin profiles on microstructures and mechanical properties of 6061 aluminum alloy by friction stir welding // Transactions of Nonferrous Metal Society of China. 2015. Vol. 25. № 9. P. 2856–2865. DOI: 10.1016/S1003-6326(15)63911-5.
21. Покляцкий А.Г. Параметры процесса сварки трением с перемешиванием тонколистовых алюминиевых сплавов // Вестник Полоцкого государственного университета. Серия B: Промышленность. Прикладные науки. 2015. № 11. С. 53–58. EDN: UOHBAH.
22. Сизова О.В., Колубаев А.В., Колубаев Е.А., Заикина А.А., Рубцов В.Е. Влияние основных параметров процесса сварки трением с перемешиванием на дефектность структуры сварного соединения // Обработка металлов (технология, оборудование, инструменты). 2017. № 4. С. 19–29. DOI: 10.17212/1994-6309-2017-4-19-29.
23. Овчинников В.В., Дриц А.М. Технологические особенности сварки трением с перемешиванием соединений из алюминиевых сплавов системы Al–Mg // Наукоемкие технологии в машиностроении. 2019. № 3. С. 7–20. DOI: 10.30987/article_5c7434ed5317f2.05345899.

Влияние геометрии инструмента на формирование сварного соединения при сварке трением с перемешиванием алюминиевого сплава АМг5

Зыбин Игорь Николаевич*[1], кандидат технических наук, доцент,
доцент кафедры «Технологии соединения и обработки материалов»
Бузырева Дарья Алексеевна, магистрант
Калужский филиал Московского государственного технического университета имени Н.Э. Баумана, Калуга (Россия)

***E-mail:** igor.zybin@bmstu.ru,
igor.zybin@mail.ru

[1]ORCID: https://orcid.org/0000-0002-5738-4231

Поступила в редакцию 18.10.2023 *Принята к публикации 08.02.2024*

Аннотация: Одним из важных параметров, влияющих на формирование сварного шва при сварке трением с перемешиванием, является геометрия инструмента, которая влияет на процессы тепловыделения и перемешивания металлов в зоне соединения. От протекания этих процессов зависит получение качественного и прочного сварного соединения без дефектов сплошности. В связи с этим представляется актуальным анализ влияния геометрии инструмента на параметры режима сварки, при которых сварное соединение формируется без дефектов сплошности, а также на прочность сварного соединения при статическом растяжении. В работе рассмотрено влияние цилиндрической и конической форм пина инструмента, а также конической формы пина с резьбой на наружной поверхности и спиральной канавкой на торцевой поверхности заплечика инструмента на параметры режима сварки, при которых сварное соединение формируется без дефектов сплошности. Показано, что изменение формы рабочей поверхности пина с цилиндрической на коническую не оказало влияния на диапазон параметров режима сварки, при которых сварное соединение формируется без дефектов сплошности. Установлено, что наличие резьбы на наружной поверхности пина и канавки на торцевой поверхности заплечика позволяет получать сварные соединения без дефектов сплошности в более широком диапазоне параметров режима сварки по сравнению с более простой геометрией инструмента. Рассмотрена макроструктура сварных соединений, полученных при использовании различных геометрических форм инструмента. Установлено, что рассмотренная геометрия инструмента практически не влияет на максимальные значения прочности сварных соединений, полученных сваркой трением с перемешиванием, и достигает 95 % от прочности основного металла.

Ключевые слова: сварка трением с перемешиванием; АМг5; геометрия инструмента; прочность сварного соединения без дефектов сплошности.

Для цитирования: Зыбин И.Н., Бузырева Д.А. Влияние геометрии инструмента на формирование сварного соединения при сварке трением с перемешиванием алюминиевого сплава АМг5 // Frontier Materials & Technologies. 2024. № 2. С. 43–52. DOI: 10.18323/2782-4039-2024-2-68-4.