Obrabotka metallov (tekhnologiya, oborudovanie, instrumenty) = Metal Working and Material Science. 2021 vol. 23 no. 3 pp. 72–83
ISSN: 1994-6309 (print) / 2541-819X (online)
DOI: 10.17212/1994-6309-2021-23.3-72-83

NSTU NETI

Obrabotka metallov -
Metal Working and Material Science

Journal homepage: http://journals.nstu.ru/obrabotka_metallov

On the problem of tool destruction when obtaining fixed joints of thick-walled aluminum alloy blanks by friction welding with mixing

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ARTICLE INFO

Article history:
Received: 15 June 2021
Revised: 30 June 2021
Accepted: 30 July 2021
Available online: 15 September 2021

Keywords:
Friction stir welding
Welding tool
Aluminum alloy
Destruction

Funding
The results were obtained in the framework of the Integrated Project “Establishment of production of high-tech large-sized equipment for intelligent adaptive friction stir welding for the aerospace and transport industries of the Russian Federation” (Agreement No. 075-11-2019-033 dated November 22, 2019) implemented by the NSTU and ISPMS SB RAS at the financial support of the Ministry of Education and Science of the Russian Federation as part of Decree of the Government of the Russian Federation No. 218 dated April 09, 2010.

Acknowledgements
Research were conducted at core facility “Structure, mechanical and physical properties of materials”.

ABSTRACT

Introduction. Among the technologies for manufacturing rocket and aircraft bodies, marine vessels, and vehicles, currently, more and more attention is paid to the technology of friction stir welding (FSW). First of all, the use of this technology is necessary where it is required to produce fixed joints of high-strength aluminum alloys. In this case, special attention should be paid to welding thick-walled blanks, as fixed joints with a thickness of 30.0 mm or more are the target products in the rocket-space and aviation industries. At the same time, it is most prone to the formation of defects due to uneven heat distribution throughout the height of the blank. It can lead to a violation of the adhesive interaction between the weld metal and the tool and can even lead to a destruction of the welding tool. The **purpose of this work** is to reveal regularities of welding tool destruction depending on parameters of friction stir welding process of aluminum alloy AA5056 fixed joints with a thickness of 35.0 mm. Following **research methods** were used in the work: the obtaining of fixed joints was carried out by friction welding with mixing, the production of samples for research was carried out by electric erosion cutting, the study of samples was carried out using optical metallography methods. **Results and discussion.** As a result of performed studies, it is revealed that samples of aluminum alloy with a thickness of 35.0 mm have a heterogeneous structure through the height of weld. There are the tool shoulder effect zone and the pin effect zone, in which certain whirling of weld material caused by the presence of grooves on tool surface is distinctly distinguished. It is shown that the zone of shoulders effect is the most exposed to the formation of tunnel-type defects because of low loading force and high welding speeds. It is revealed that tool destruction occurs tangentially to the surface of the tool grooves due to the high tool load and high welding speeds.

For citation: Kalashnikov K.N., Chumaevskii A.V., Kalashnikova T.A., Ivanov A.N., Rubtsov V.E., Kolubaev E.A., Bakshaev V.A. On the problem of tool destruction when obtaining fixed joints of thick-walled aluminum alloy blanks by friction welding with mixing. *Obrabotka metallov (tekhnologiya, oborudovanie, instrumenty) = Metal Working and Material Science*, 2021, vol. 23, no. 3, pp. 72–83. DOI: 10.17212/1994-6309-2021-23.3-72-83. (In Russian).

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Introduction

Friction stir welding (FSW) is a process in which the joining of workpieces of different materials (such as aluminum and titanium alloys, bronze, steel, etc.) occurs with no liquid phase formation [1–3]. The welding process is carried out by introducing a specially designed rotating tool under a loading force into the butt of two rigidly fixed workpieces. It moves along with the butt line and forms a welded joint. The main advantage of the FSW method is that the tool heats the workpiece material to a temperature of about 0.6–0.8 of the melting point. As a result, the material is plasticized, fragmented, and gripped and due to adhesive interaction, is captured by the tool and transferred layer by layer, forming a weld [4–6]. Depending on the alloy to be welded, welding tools are made with high-speed steels [7, 8], heat-resistant nickel-based alloys [9], and other materials. It ensures both the tools' ability to withstand the thermal conditions and optimal adhesion-diffusion interaction to form the stir zone. Since the process occurs in the solid phase, it has found an application in the aircraft and spacecraft industries, particularly for the welding of high-strength aluminum alloys [10, 11]. But, in most cases, the manufacture of aerospace components requires welding of thick-walled workpieces with subsequent mechanical processing to ensure the strong and most rigid construction. In this regard, a problem arises associated with obtaining high-quality welded joints with a thickness of 30.0 mm and more: the temperature effect of the tool in the welding zone is uneven, which requires fine control of FSW parameters, as well as the selection of the optimal shape of the welding tool [12]. The work [13] shows that during the welding of thick workpieces, the grain size in the stir zone changes throughout the height of the weld. It leads to a decrease in microhardness from top to bottom of the stir zone. In addition, in [14], attempts were made to optimize the heating of the welded material of workpieces up to 25.0 mm thick by preheating using a specially designed substrate and a laser heating device. However, the additional heating also affects the selection of welding parameters. As a result of poorly selected parameters, there are defects in the welded joint such as voids, tunnel-type flaws, and butt lines (Lazy S) [15–20], besides there is a possibility of welding tool destruction. Therefore, in the present work, a study of 35.0 mm thick welded joints made of aluminum alloy AMg5 by friction stir welding is carried out in order to reveal the regularities of the formation of defects in the mixing zone and destruction of the welding tool, depending on the parameters of the FSW process.

Methods

The samples for the research were obtained on the special equipment for friction stir welding at CJSC "Cheboksary Enterprise Sespel" Cheboksary, Russia. Welding tools made of high-speed steel with shoulders with a diameter of 50 mm and a movable pin up to 35 mm long were used for the form welded joints. The tool pin had a conical shape with helical grooves, and three surfaces flattened at an angle of 120º. The samples were welded in four modes, presented in Table 1. The scheme of friction welding with mixing with the destruction of the tool and the scheme of cutting samples for research are shown in Figure 1. The fored welds were subjected electrical discharge machining to obtain research samples in the longitudinal and cross-section of the weld using the DK7750 machine. The samples for metallographic studies were sanded on abrasive paper, polished using diamond paste and subjected to chemical etching in Keller reagent to reveal the microstructure of the material.

Samples of the material with the tool stuck in the mixing zone were additionally etched in an aqueous solution of nitric acid (HNO_3). Metallographic studies were carried out on an optical microscope Altami MET 1C.

Results and discussion

As a result, by the method of friction welding with mixing, samples of welded joints were obtained using four modes that differ in the loading force and welding speeds (travel speed and the speed of the tool rotation). Figure 2 shows panoramic images of the sample mixing zone in cross-section. When welding

Table 1

Friction stir welding parameters

Sample number	Loading force *P*, kg	Tool travel speed, *V*, mm/min	Tool rotation rate, ω, rpm	Tool pitch angle, Deg.
1	3700	60	300	2,5
2	3900	65	300	2,5
3	4100	60	280	2,5
4	4100	60	260	2,5

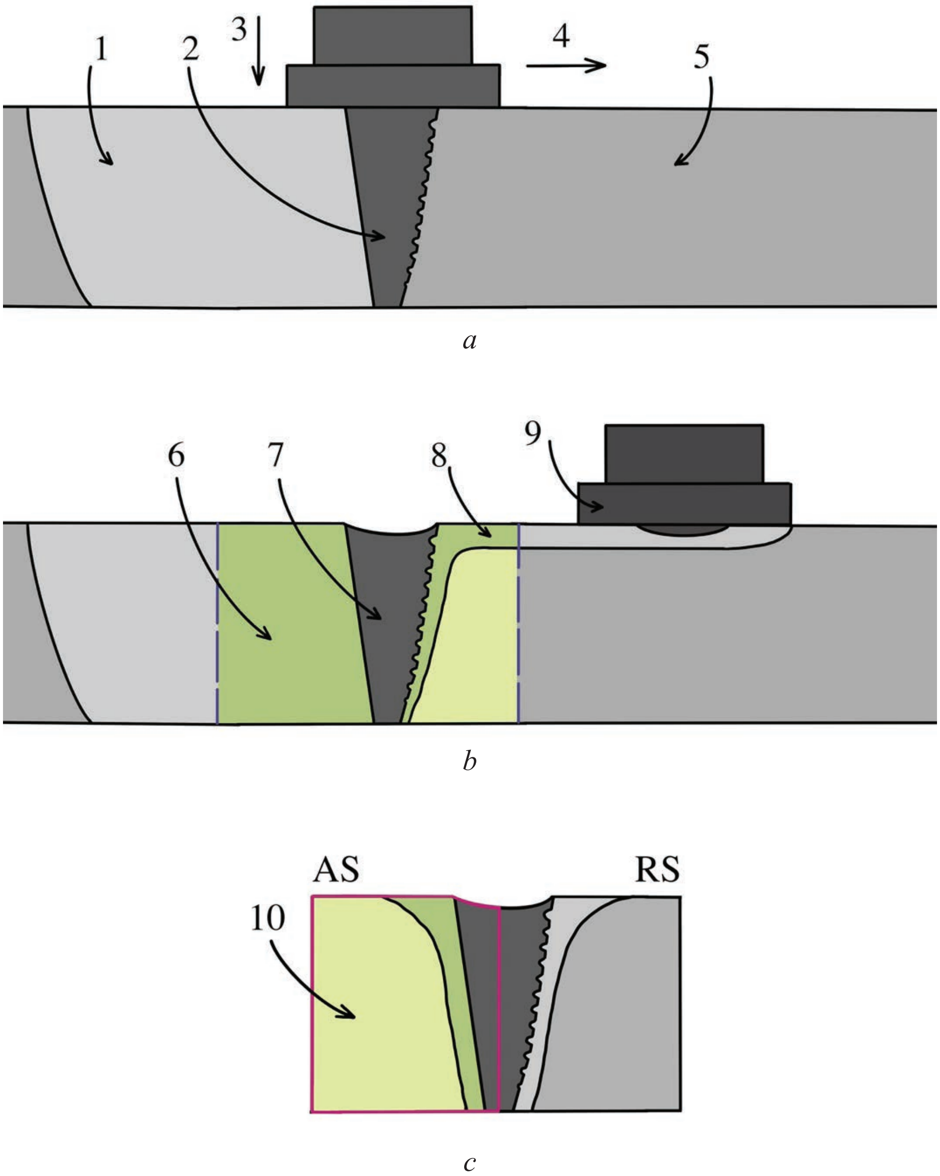


Fig. 1. Scheme of friction stir welding in the longitudinal section (*a*), cutting of metallographic samples after tool destruction in the longitudinal section (*b*) and transverse section (*c*):

1 – stir zone; *2* – tool pin; *3* – tool loading force; *4* – direction of tool movement; *5* – base metal; *6* – longitudinal metallographic section; *7* – a stuck piece of tool; *8* – stir zone of remaining tool part; *9* – remaining tool part; *10* – transverse metallographic section

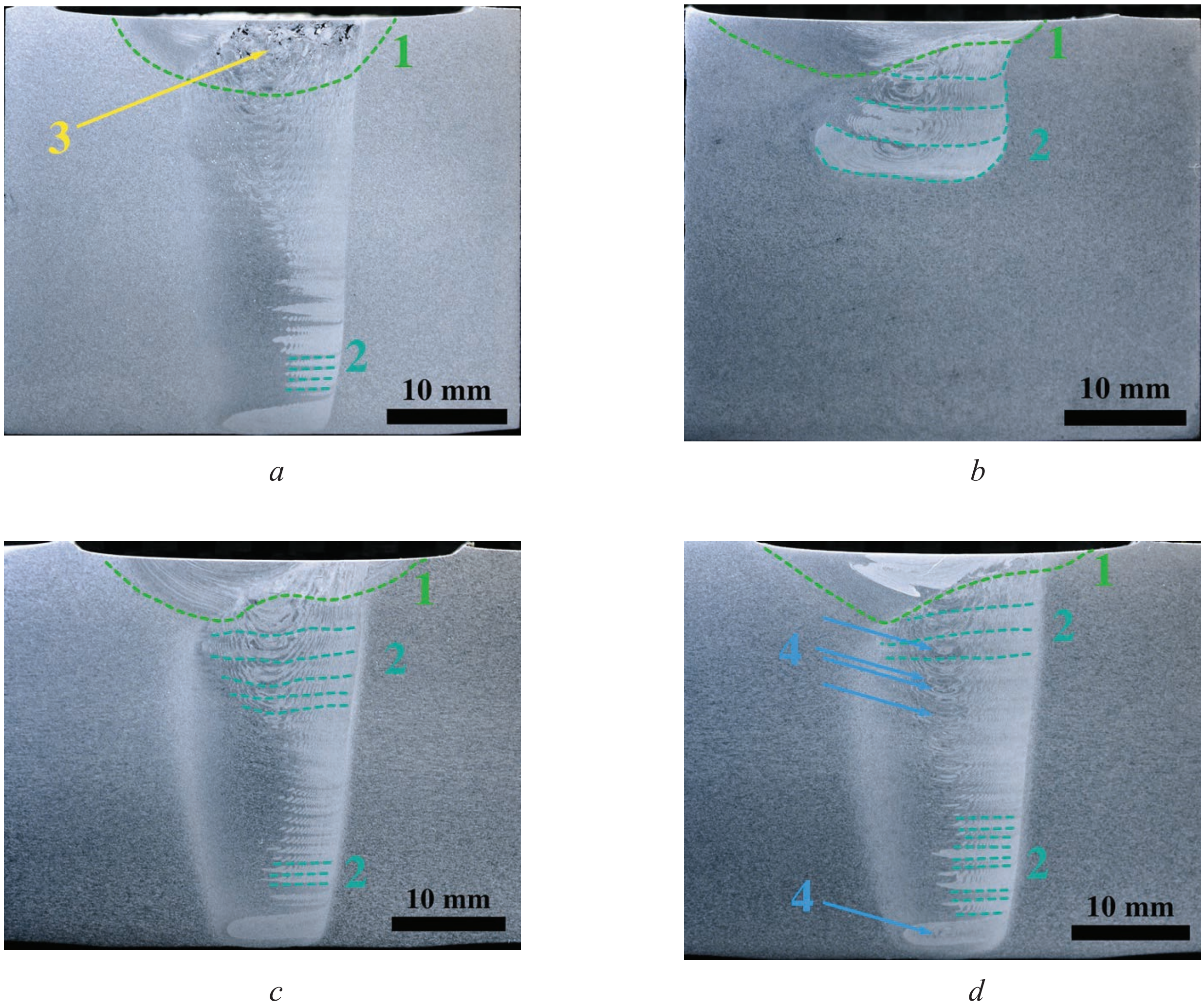


Fig. 2. Panoramic images of the stir zone of welded joints produced by modes 1 (*a*), 2 (*b*), 3 (c) and 4 (d) in cross-section:

1 – tool shoulder affected zone; *2* – stir zones formed by tool grooves; *3* – defects of the welded joint; *4* – weld cores formed by local material flows

samples 2 and 4, the tool was destroyed, and in sample 2 – at an early stage of the process. In this regard, Figure 2b shows the cross-section in the area after the tool destruction.

As can be seen from the figure, sample 1, obtained at high welding speeds, has the narrowest mixing zone, while in samples 3 and 4 the mixing zone is wider, with a clearly different zone of influence of the tool shoulders and concentric rings, also known as “onion rings”, forming the core of the welded joint [21]. It is worth noting that, unlike welded joints with a thickness of up to 10 mm, a large number of small cores are formed, not a single seam core.

This character of the mixing zone formation is due to the uneven heating of the weld material in height [14], which leads to inhomogeneity of the adhesive interaction of the material with the tool being welded. As a result, the transfer layer is divided into smaller ones, mainly carried by the grooves of the tool, which is clearly seen in Figure 2, *b*, *d*: in the lower part of the weld, strips of separately transferred material are allocated, which, nevertheless, have a periodic nature.

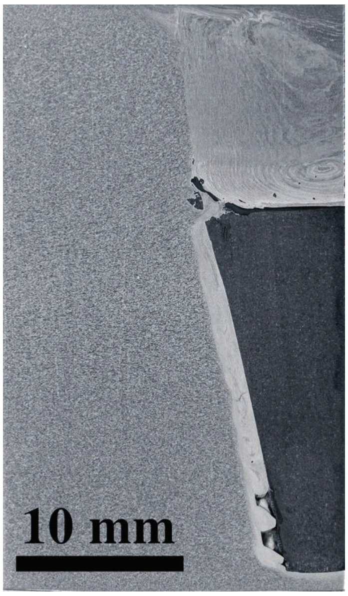
Figure *2a* shows that in Sample 1, a structure with tunnel-type defects and voids was formed in the zone of influence of the tool shoulders. High welding speeds with a relatively low loading force led to the fact that the thermal conditions for the formation of transfer layers were violated in the upper part of the sample. In turn, this led to a deterioration of the adhesive interaction during the welding process. However, in this case, the destruction of the tool did not occur, whereas when welding sample 2, obtained at a higher loading force and speed of movement, the destruction occurred at the initial stage of welding. Figure 3 shows the tool fragment in sample 2 and the longitudinal section of the mixing zone formed by the remaining part of the tool.

As can be seen from Figure 3, an increase in the load allowed to eliminate the defect in the area under the tool shoulders, but probably increased the resistance of the base metal to the tool when moving during welding. Figure 3, *b*, made in the longitudinal section of the sample, confirms the influence of the tool grooves on the formation of separate flows of material around the tool. Consequently, local metal flows affect the area of the grooves, creating stresses there that are tangential to its surface.

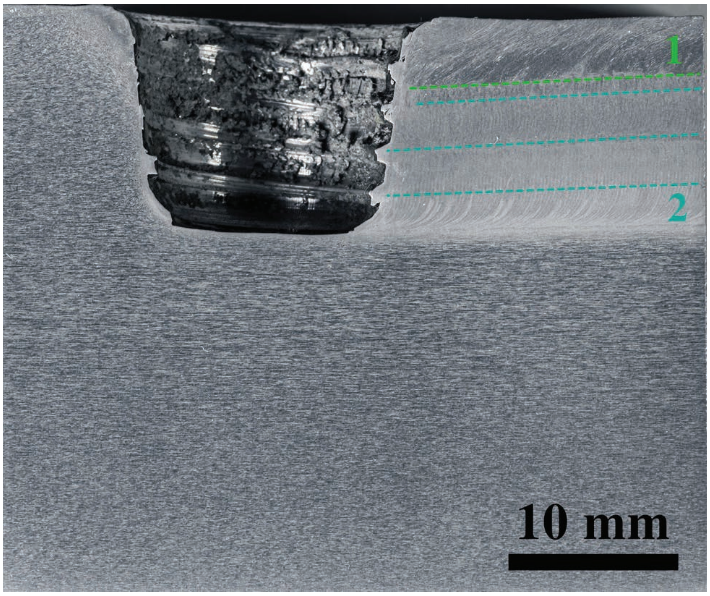
In sample 4, made with a high loading force, but lower speeds of movement and rotation of the tool, a similar picture is observed. Figure 4 shows that before the destruction of the tool, the mixing zone was formed by separate flows of material formed by the shoulders (*1* in Fig. 4, *a*) and the tool grooves, while the height of the transfer layers decreases towards the middle of the weld (3) and again increases slightly towards the lower part (4). Thus, the action of local material flows in the area of the tool grooves proceeds independently of the selected mode, but its intensity is determined by both the loading force and the welding speeds.

At the same time, sample 3, obtained with a loading force and a tool movement speed like that of sample 4 (4100 kg and 60 mm/min, respectively), but at a higher rotation speed (280 rpm vs. 260 rpm), demonstrates both the absence of any weld defects and a fully completed welding process without the welding tool destruction.

After the tool destruction, a strongly deformed zone is observed on the stuck part, represented by a layered structure (Fig. 5, *b*), and the closer to the contact area between the stuck and the remaining parts of the tool, the material delamination becomes more intense and is accompanied by the formation of cracks parallel to the plane of delamination. At the same time, in the area below the delamination zone, cracks spread deep into the tool, the length of which can reach 20 mm or more (Fig. 5, *b, c*). As a result of mutual wear during friction contact, inclusions of tool fragments of two types are mixed into the mixing zone: inclusions having the structure of a strongly deformed layered region, and inclusions with the structure of an initial tool material structure (Fig. 5, *a*). It is obvious that such inclusions are products of tool wear, while during the wear process the remaining (movable) part of the tool does not undergo significant plastic deformation necessary to change the structure of the material.



a



b

Fig. 3. Cross-section of sample No. 2 with the stuck piece of tool (*a*) and longitudinal cross–section of sample No. 2 in the tool outlet zone (*b*):

1 – stir zone formed by tool shoulders; *2* – stir zones formed by tool grooves

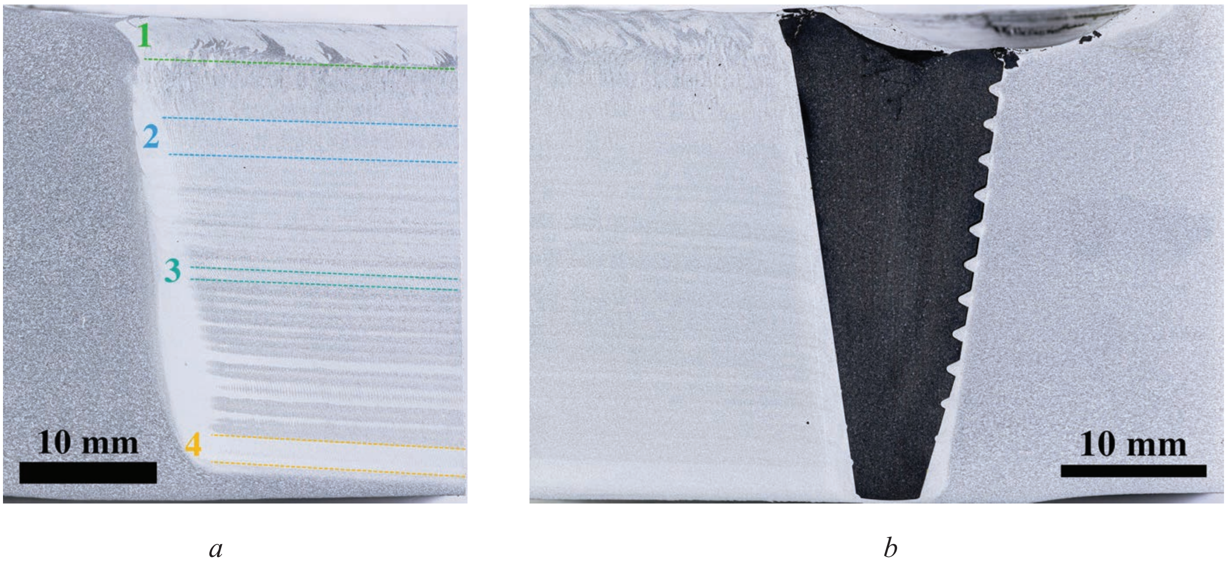


Fig. 4. Longitudinal cross-section of sample No. 4 with the stuck piece of tool at the beginning (*a*) and the end of the weld (*b*):

1 – stir zone formed by tool shoulders; stir zone formed by tool groove; *2* – in the upper part of the weld; *3* – in the middle of the weld; *4* – in the lower part of the weld

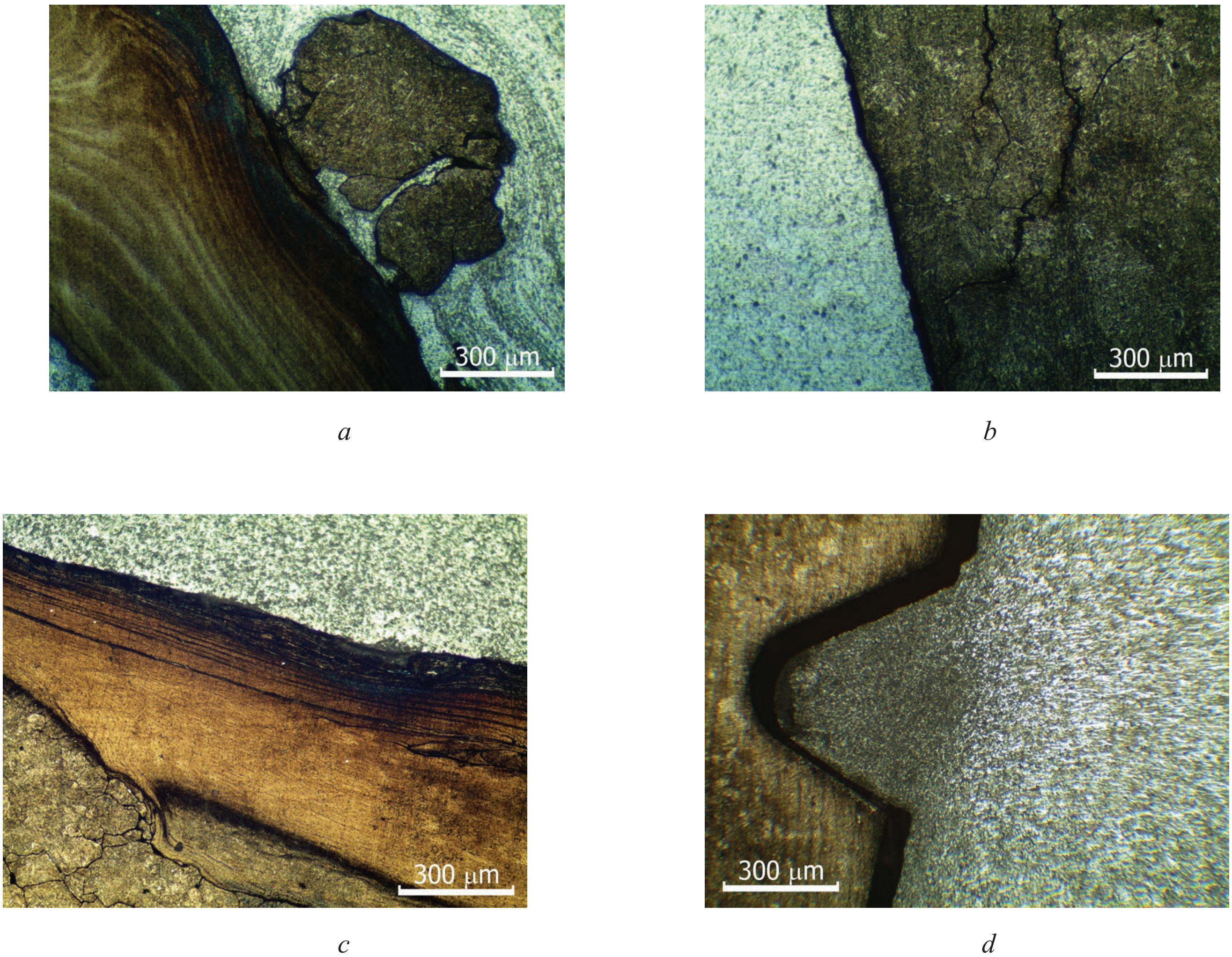


Fig. 5. Magnified images of the tool fragments in the sample No. 2 (*a, b*) and in sample No. 4 (*c, d*)

From the panoramic image in Figure 4, *b* and the enlarged image in Figure 5*, g*, it can be seen that the inhomogeneity of the temperature effect has a significant impact on the fragmentation of the material and the formation of transfer layers in the area in front of the tool during friction mixing welding. The result of such heterogeneity is a change in the width of the zone of the primary fragmented material. So, in the upper part of the tool, the width of this zone is minimal and is only 0.22 mm to the surface of the tool, while in the lower part of the tool, its width increases to 1.28 mm. From Figure 4*, b*, it can be concluded that the depth of the tool grooves affects the fragmentation of the material during welding, since where the depth of the grooves is maximum – the width of the zone of the primary fragmented material is minimal. At the same time, in the lower part, where the greatest thickness of the fragmentation zone is observed, the depth of the grooves is minimal.

Figure 4 shows that the destruction of the tool in sample 4 occurred in the upper part, that is, in the zone where the temperature effect of the tool on the material is minimal. In this case, the fracture of the tool has a spherical shape. As discussed above, local flows of material resist the movement of the tool in the area of the grooves, thereby increasing the tangential stresses in these zones [22]. The shape of the fracture surface of the tool and the low intensity of fragmentation and plasticization of the material in the area in front of the tool led to the fact that the stresses acting tangentially to the surface of the groove under the shoulders of the tool reached a certain critical value, as a result of which the formation of a crack began, which led to the destruction of the tool. Probably, in sample 2, the destruction process proceeded according to a similar pattern. However, in this case, the destruction occurred in the middle of the weld, which may be due to the fact that the local flows of the transferred material are formed in this area with the narrowest height (as shown in Figure 4 in the cross section of the weld).

Thus, both the welding speeds and the loading force on the tool have a serious impact on the stability of the friction welding process with mixing and the welding tool when obtaining permanent joints with a thickness of 35 mm. At low loading force, but high welding speeds, a defective welded joint is formed with the presence of tunnel-type defects in the zone of influence of the tool shoulder due to the deterioration of the adhesive interaction of the material being welded with the tool. An increase in the load makes it possible to eliminate the defect, but at high welding speeds it leads to tool failure due to an increase in the resistance of the material to the movement of the tool and the formation of narrow local flows of material due to the shape of the tool. In order to stabilize the influence of the parameters, the load on the tool was increased, and the process speeds were reduced, which made it possible to obtain a defect-free welded joint without destroying the tool. However, a further decrease in the rotation speed again leads to the tool destruction due to the fact that the set speed does not provide the required thermal welding conditions in the mixing zone, due to which the width of the zone of primarily fragmented and plasticized material is very small in the upper part of the weld, which also leads to an increase in the resistance of the material being welded to the tool.

Conclusion

As a result of the conducted studies, it became possible to choose the optimal mode for obtaining an all-in-one joint of the AMg5 aluminum alloy with a thickness of 35 mm by friction welding with mixing, as well as to establish the dependence of the formation of defects and destruction of the tool on the parameters of the welding process. It was found that the loading force of the tool is the determining factor for the formation of tunnel-type defects and voids in the area under the tool shoulders. The destruction of the tool is affected by both the loading force and the speed of movement and rotation of the tool, but the main parameter in this case is the speed of rotation. At an excessively high rotation speed, the tool is destroyed in the middle part of the weld, where local volumes of the transferred material are formed by the tool grooves. At a low speed of rotation of the tool, the destruction occurs in the area under the tool shoulders and is caused by an inhomogeneous temperature effect during the welding process. In both cases, the destruction of the tool occurs tangentially to the surface of the tool groove, since the recesses on the surface of the tool experience the greatest tangential stresses caused by the increased resistance of the material being welded to the tool.

References

1. Mishra R.S., Ma Z.Y. Friction stir welding and processing. *Materials Science and Engineering: R: Reports*, 2005, vol. 50, iss. 1, pp. 1–78. DOI: 10.1016/j.mser.2005.07.001.

2. Threadgill P.L., Leonard A.J., Shercliff H.R., Withers P.J. Friction stir welding of aluminium alloys. *International Materials Reviews*, 2009, vol. 54, iss. 2, pp. 49–93. DOI: 10.1179/174328009X411136.

3. Yu P., Wu C., Shi L. Analysis and characterization of dynamic recrystallization and grain structure evolution in friction stir welding of aluminum plates. *Acta Materialia*, 2021, vol. 207, p. 116692. DOI: 10.1016/j.actamat.2021.116692.

4. Eliseev A.A., Kalashnikova T.A., Filippov A.V., Kolubaev E.A. Material transfer by friction stir processing. Multiscale biomechanics and tribology of inorganic and organic systems: in memory of Professor Sergey Psakhie. Ed. by G.-P. Ostermeyer, V.L. Popov, E.V Shilko., O.S. Vasiljeva. Cham, Springer International Publishing, 2021, pp. 169–188. DOI: 10.1007/978-3-030-60124-9_8.

5. Sahlot P., Singh A.K., Badheka V.J., Arora A. Friction stir welding of copper: numerical modeling and validation. *Transactions of the Indian Institute of Metals*, 2019, vol. 72, iss. 5, pp. 1339–1347. DOI: 10.1007/s12666-019-01629-9.

6. Hwang Y.M., Fan P.L., Lin C.H. Experimental study on friction stir welding of copper metals. *Journal of Materials Processing Technology*, 2010, vol. 210, iss. 12, pp. 1667–1672. DOI: 10.1016/j.jmatprotec.2010.05.019.

7. RajKumar V., VenkateshKannan M., Sadeesh P., Arivazhagan N., Ramkumar K.D. Studies on effect of tool design and welding parameters on the friction stir welding of dissimilar aluminium alloys AA 5052 – AA 6061. *Procedia Engineering*, 2014, vol. 75, pp. 93–97. DOI: 10.1016/j.proeng.2013.11.019.

8. Tarasov S.Y., Rubtsov V.E., Kolubaev E.A. A proposed diffusion-controlled wear mechanism of alloy steel friction stir welding (FSW) tools used on an aluminum alloy. *Wear*, 2014, vol. 318, iss. 1, pp. 130–134. DOI: 10.1016/j.wear.2014.06.014.

9. Amirov A., Eliseev A., Kolubaev E., Filippov A., Rubtsov V. Wear of ZhS6U nickel superalloy tool in friction stir processing on commercially pure titanium. *Metals*, 2020, vol. 10, iss. 6, p. 799. DOI: 10.3390/met10060799.

10. Burford D., Widener C., Tweedy B. Advances in friction stir welding for aerospace applications. *6th AIAA Aviation Technology, Integration and Operations Conference (ATIO)*, Reston, Virginia, American Institute of Aeronautics and Astronautics, 2006. DOI: 10.2514/6.2006-7730.

11. Longhurst W.R., Cox C.D., Gibson B.T., Cook G.E., Strauss A.M., Wilbur I.C., Osborne B.E. Development of friction stir welding technologies for in-space manufacturing. *The International Journal of Advanced Manufacturing Technology*, 2017, vol. 90, iss. 1, pp. 81–91. DOI: 10.1007/s00170-016-9362-1.

12. Aissani M., Gachi S., Boubenider F., Benkedda Y. Design and optimization of friction stir welding tool. *Materials and Manufacturing Processes*, 2010, vol. 25, iss. 11, pp. 1199–1205. DOI: 10.1080/10426910903536733.

13. Avettand-Fenoel M.-N., Taillard R. Heterogeneity of the nugget microstructure in a thick 2050 Al friction-stirred weld. *Metallurgical and Materials Transactions: A*, 2015, vol. 46, iss. 1, pp. 300–314. DOI: 10.1007/s11661-014-2638-x.

14. Imam M., Sun Y., Fujii H., Aoki Y., MA N., Tsutsumi S., Murakawa H. Friction stir welding of thick aluminium welds–challenges and perspectives. *Friction Stir Welding and Processing IX*. Ed. by Y. Hovanski, R. Mishra, Y. Sato, P. Upadhyay, D. Yan. Cham, Springer, 2017, pp. 119–124. DOI: 10.1007/978-3-319-52383-5_13.

15. Das B., Pal S., Bag S. Defect detection in friction stir welding process using signal information and fractal theory. *Procedia Engineering*, 2016, vol. 144, pp. 172–178. DOI: 10.1016/j.proeng.2016.05.021.

16. Koilraj M., Sundareswaran V., Vijayan S., Koteswara Rao S.R. Friction stir welding of dissimilar aluminum alloys AA2219 to AA5083 – Optimization of process parameters using Taguchi technique. *Materials and Design*, 2012, vol. 42, pp. 1–7. DOI: 10.1016/j.matdes.2012.02.016.

17. Kah P., Rajan R., Martikainen J., Suoranta R. Investigation of weld defects in friction-stir welding and fusion welding of aluminium alloys. *International Journal of Mechanical and Materials Engineering*, 2015, vol. 10, iss. 1, p. 26. DOI: 10.1186/s40712-015-0053-8.

18. Al-Moussawi M., Smith A.J. Defects in friction stir welding of steel. *Metallography, Microstructure, and Analysis*, 2018, vol. 7, iss. 2, pp. 194–202. DOI: 10.1007/s13632-018-0438-1.

19. Wang G., Zhao Y., Hao Y. Friction stir welding of high-strength aerospace aluminum alloy and application in rocket tank manufacturing. *Journal of Materials Science and Technology*, 2018, vol. 34, iss. 1, pp. 73–91. DOI: 10.1016/j.jmst.2017.11.041.

20. Dialami N., Cervera M., Chiumenti M. Defect formation and material flow in Friction Stir Welding. *European Journal of Mechanics: A, Solids*, 2020, vol. 80, p. 103912. DOI: 10.1016/j.euromechsol.2019.103912.

21. Chen Z.W., Cui S. On the forming mechanism of banded structures in aluminium alloy friction stir welds. *Scripta Materialia*, 2008, vol. 58, iss. 5, pp. 417–420. DOI: 10.1016/j.scriptamat.2007.10.026.

22. Ávila R.E. A variational model for shear stress in friction stir welding based on the weld shape in transverse sections. *Modelling and Simulation in Materials Science and Engineering*, 2006, vol. 14, iss. 4, pp. 689–702. DOI: 10.1088/0965-0393/14/4/011.

Conflicts of Interest

The authors declare no conflict of interest.