New ecologic method for joining of titanium alloys

L.-N. Boțilă[a*], **R. Cojocaru**[b], **C. Ciucă**[c]

National Research & Development Institute for Welding and Material Testing - ISIM Timisoara, Romania

E-mail: [a*]*lbotila@isim.ro*, [b]*rcojocaru@isim.ro*, [c]*cciuca@isim.ro*

Keywords

Ecologic method, joining, friction stir welding, titanium alloys

1. Introduction

Due to its favorable strength and density ratio, titanium and its alloys are used in aerospace, but also in the automotive industry. Having good corrosion resistance to a number of chemical environments, these materials are also used in chemistry and nuclear engineering.

Titanium is commonly used in industrial applications due to its corrosion protection properties, as well as for high performance structures that require a high strength / weight ratio or work at high temperatures. Pure, low-strength commercial grade titanium is used for applications where only corrosion resistance is required, while high-strength alloys are used to build structures. Even if the titanium alloys are about 10-15 times more expensive than stainless steel and aluminum, these alloys are the first to be used when the performance of the application is more important than the cost of the application [1]. According to the American Metals Society (ASM) 70-80% of the titanium used in the USA is intended for use in the aerospace industry [2].

Titanium and its alloys have the following general characteristics:

- Can be welded and processed;
- Light weight – 50% less compared with the steel weight;
- Resistance to fire and shocks;
- Favorable cryogenic properties;
- Biocompatible and non-toxic material;
- Nuclear safety and the environmental safety.

In most industrial applications, titanium has replaced other materials. As a safe material, the systems and components in which titanium was used are more durable, performance and lifespan have substantially exceeded expectations, in many situations.

There are important limitations to the possibility of industrial use of titanium when fusion welding is required, due to the characteristics, properties and welding behavior of titanium. Also, the limitations are present even more when dissimilar welding joints of titanium with other metallic materials are required.

Welding and other joining techniques of titanium and its alloys have become very important in order to be able to use these materials to fabrication of products from various top industrial sectors.

Although titanium alloys are generally weldable, problems can arise due to the surface oxidation and component deformation, which causes a poor quality of welds. In addition, some of the most complex types of Ti alloys are difficult to join with conventional fusion welding techniques [3], [4]. Welding of titanium alloys by the FSW process is a challenge, due to the high mechanical strength characteristics, high melting temperature and very low thermal conductivity [5].

Significant groups of researchers have approached the FSW welding of titanium and its alloys to analyze the microstructure issues and the mechanism of joint formation in the mixing area [6] - [17].

At worldwide level, there is a particular interest to use of titanium alloys, especially in aeronautics and aerospace [18]-[20], in applications where FSW welding of titanium alloys can bring the following benefits:

- making high-quality solid state welds;
- welds with excellent mechanical properties;
- reduced distortion of welded components;
- high efficiency and low energy consumption welding process;
- the possibility of joining Ti alloys (certain material conditions) that cannot be joined by fusion welding processes.

By using the friction stir welding process, which is a solid state welding process, reaching the melting point of the material is avoided and the problems which occur to the titanium welding can be reduced.

Researches regarding FSW welding of titanium alloy are in continuous development to find new variants and technical joining solutions, to optimize the joining processes, to extend the applicability areas and to identify new couples of materials to which to be able to apply FSW welding, etc. [21].

2. Aspects regarding FSW welding of titanium alloys

FSW welding of titanium alloys requires additional preparations, conditions and precautions, compared to FSW welding of aluminum and copper alloys or steels.

One problem is the reactivity of Ti welding parts at high temperatures. Titanium has a high affinity for interstitial contamination at temperatures above 480°C. Most fusion welding technologies attempt to keep the level of contamination below 10 PPM, and this is also true for FSW. Oxygen that occurs due to insufficient protection or poor quality of protective gas, may cause the α phase occurrence on the weld surface [22]. The welding tool tends to oxidize to air at high temperatures and could become brittle during welding without gas protection.

Backing plate

When choosing the material for backing plate, the particularities of the FSW welding of Ti alloys must be taken into account. Temperature and pressure requirements are similarly to those of the welding tools materials. Refractory and ceramic alloys are recommended for the construction of the backing plate. Where appropriate, an ordinary stainless steel can also be used. In this area, further researches are needed, especially for welds having complex curved shapes.

Welding tool

Materials that are not easily to be joined together using conventional welding, such as for example titanium, nickel and magnesium alloys, can be joined using the FSW process [23]. For these categories of materials, FSW welding tools should be chosen taking into account the characteristics and properties of the materials to be joined, as well as a number of criteria for choosing the adequate material for the welding tool.

- *General considerations regarding the selection of the welding tool material*

Correct selection of the tool material requires knowledge of material characteristics that are important to each FSW application. Many of the material characteristics are considered important for FSW welding, but their choice depends on the materials to be joined, estimated lifetime of the tool and the operator experience. In addition to the physical properties of the material, there are some practical considerations that contribute to the choice of the tool material [24].

A) Resistance to ambient and high temperature

The welding tool material must be capable of withstanding the compressive forces that occur when the tool comes into contact with the materials to be welded and to have sufficient compressive and shear strength at elevated temperatures to prevent distortion or even breakage of the tool during the welding process [24]-[26]. Typically, setting the requirements for the tool's material resistance requires complex simulations. Minimum requirements for the strength of the tool material imply that the mechanical strength at high temperatures should be greater than the forces that acting on the tool.

B) Stability at high temperatures

In addition to resistance to the high temperatures, the welding tool must maintain its strength properties and dimensional stability during use [24]-[26].

The creep fatigue is taken into account for long-length welds, where due to the low creep resistance, dimensional changes of the tool can occur. The properties of the tool material and the FSW welding conditions determine the maximum operating temperature of the tool. Tools used above the temperature considered as maximum admissible, will lead to a deterioration of the mechanical properties. Changes in mechanical properties arise due to the aging, recovery and restoration of the dislocation substructures. For FSW welding, the microstructural changes will cause the tool thermal recovery and tool shape changes or even its breakage. Thermal fatigue resistance must be considered when FSW tools are subject to numerous heating and cooling cycles. However, in most cases, other characteristics of the tool material will cause cracking before the thermal fatigue occurs.

C) Wear resistance

Excessive wear of the tool changes the tool shape, contributing to the change in welding quality and increasing the probability of defects occurrence [23], [24], [26], [27]. In FSW welding, the wear of the tool may occur as adhesive, abrasive or chemical wear (occurs due to chemical reactivity). The tool wear mechanisms depend on the interaction between the work pieces and the tool material, as well as the tool parameters. For example, for PCBN tools, wear at low speed is caused by adhesive wear, while wear at high speeds is caused by abrasive wear [24].

D) Tool reactivity

The tool material must not react with the workpiece material or with the environment, otherwise will have a negative effect of the tool surface properties. For example, titanium is known to be a reactive material at high temperatures, however any titanium reaction with the tool material will change the properties of the tool and reduce the quality of the welded joint. The reaction of the tool with the environment, for example oxidation, can modify the wear resistance of the tool or even produce toxic substances (e.g. MoO_3). The reaction of the tool with the environment can be limited by using protective gases, but these require a more complex welding system [24], [26], [28], [29].

E) Breaking resistance

The breaking resistance of the tool plays a significant role at the moment of impact with the materials to be welded and during the actual plunging in them. The local tensions produced when the tool comes into contact with the materials to be joined are enough large to break the tool, even if the following methods are used: pilot holes, low plunging speeds, preheating of the parts. At the moment of impact and during plunging, the greatest damages to the tool are produced [24]. When selecting the tool, it takes into account that the ceramic tools can break faster than tools made of other materials.

F) Coefficient of thermal expansion

Thermal expansion is important for tools made from dissimilar materials. Large differences in the coefficient of thermal expansion between the pin tool and the tool shoulder materials cause the shoulder expand towards the pin and vice versa. Both situations lead to increase the tensions between the shoulder and the pin tool, which causes damage or even breakage of the tool. A similar situation occurs when the shoulder and the pin tool are made of the same material, but the welding tool holder part o is made of a different material. One method of solve this issue is to create a thermal barrier to prevent the heat transfer from the shoulder and the pin tool to the tool holder. An example of this are represented by the tools made of PCBN (Polycrystalline Cubic Boron Nitride) material, where a thermal barrier prevents the heat transfer to the tungsten carbide tool holder [24]. Differences in thermal expansion coefficient between tools and workpieces do not have a significant effect on the FSW welding process.

G) Machinability

Many of the FSW welding tools have geometric shapes that require machining, therefore the tool material must allow this [24], [26].

H) Uniformity in microstructure and density

The tool material must not have variations in microstructure or density. These small variations may produce a non-homogeneous area inside the tool, where premature breakage may occur [24], [26]. Powder metallic alloys are manufactured with different densities and welding tools must be made of homogeneous density materials.

- *Types of materials for FSW welding tools of titanium and titanium alloys*

For FSW welding of Ti alloys, for example, [30]-[32], refractory materials for welding tools are required, including tungsten alloys [33]-[79], based on cobalt [80]-[83], molybdenum [84]-[86] and nickel based alloys [87], high temperature resistant materials, tools made of special materials or thereof combinations, such as W-Re, W-La, WC-Co [88]-[91].

Although these welding tools materials are expensive, they are best suited to resist to the temperature developed during the FSW welding process of high melting temperature materials.

Although good results are being obtained on the large-scale industrial use of FSW tools made of PCBN (especially for welding of stainless steels and alloyed steels), the main limitations in the use of PCBN are the extremely high costs as well as the fragility of the material which can lead to unexpected failures [92]. Due to severe wear, it is not recommended to use PCBN tools [93] to weld titanium alloys, despite their good performances to the steel welding.

Tungsten welding tools appear to be the most common used for FSW welding of titanium alloys. Currently four types of tungsten alloys are used: tungsten carbides, W-Re alloys, Densimet and W-La alloys [54]. Among these materials, tools made of W carbide are the most cost-effective, with relatively good machining and chemical stability [94]. W-Re tools are characterized by the ability to work at high operating temperatures, but their fabrication is difficult and expensive [54]. The typical chemical composition of these tools is W with 25% Re, sometimes W with 5% Re or even W with 3% Re [41]-[43], [59] and [60]. Densimet is a composite material with a high content of tungsten (> 90%) and a nickel-iron binder phase. The working temperature of the Densimet tools is relatively low, having good machinability and low cost [54]. W-La tools have an optimal balance between high temperature resistance, machinability and cost [40]. The typical chemical composition of these tools is W - with 1% La_2O_3 [52], [56] and [71].

Due to the low machining capacity of the tools materials, a relatively simple geometry is usually used. Due to the relatively low thermal conductivity of the titanium alloys, the geometry with the large shoulder and the small cylindrical pin is considered inappropriate, because the heat generated by the tool shoulder is not able to reach the welding root [75]. Also, due to the high forces on the welding tool during the welding process, the relatively small diameter pin may be damaged or even broken [57]. It is therefore recommended to use a welding tool having a smaller diameter shoulder and a larger diameter conical pin [75].

W-Re welding tools requires high fabrication costs due to the fact that W and Re are very expensive metallic materials. That is why it has been attempted to make low-cost welding tools having conical pin with flat bevels, made of high strength alloys (e.g. Ni-Cr).

At ISIM Timisoara, for friction stir welding of titanium TiGr2 were used welding tools with pin made of tungsten alloys, as well as welding tools made of P20S tungsten sintered carbide (Figure 1).

FSW welding of titanium alloys usually leads to wear of FSW tools and sometimes this unwanted effect can be very pronounced. This fact reduces the tool lifespan and contaminates the joining area, reducing the quality of weld. The most severe wear of the tool often occurs at the plunging stage of the tool in materials to be welded. This effect is usually attributed to the relatively high stresses to which the welding tool is subjected.

Figure 1. Friction stir welding tools for titanium alloys, at ISIM Timisoara
a) Welding tools withpin made of tungsten alloy; b) Welding tool made of P20S, with smooth conical pin;c) Welding tool made of P20S, having conical pin with 4 flat bevels

Ti alloys have a high plasticization temperature and low thermal conductivity, making it difficult to generate enough heat in the FSW welding process to soften / plasticize the material without causing local overheating [26], [95]. Overheating may result in excessive titanium plasticization, causing the material expulsion from the welding area, when conventional FSW welding tools are used.

3. Experiments for friction stir welding of titanium TiGr2

ISIM Timisoara has developed experimental research programs for titanium TiGr2 welding.

Butt and overlap welding of TiGr2 titanium sheets were performed using the tool categories mentioned in Figure 1, as well as the characterization of welded joints, to obtain information on welding behavior and their FSW welding capabilities.

The experimental program was conducted on the FSW welding machine from ISIM endowment, which has the following main technical characteristics:

- adjustable welding speed in the range: 10 - 480 mm/min;
- the rotational speed of the welding tool - adjustable in the range: 300 - 1450 rpm;
- the useful stroke for welding: 1000 mm.

For butt and overlap FSW welding of TiGr2 titanium sheets having dimensions of 200x100x4 mm, 13 experiments were performed using the welding tool categories shown in Figure 1, as well as different welding parameters.

The following welding tool geometries were used:

- smooth cylindrical pin, having diameter Ø$_{pin}$ = 4.0 mm (tungsten alloy with 2% La_2O_3 - WL20) and Ø$_{pin}$ = 5.0 mm (tungsten alloy with 2% ThO_2-WT20), pin lengths L_{pin} = 2.8 mm; 3.0 mm and 3.8 mm; the tool's shoulder is made of X40CrMoV5 material, with diameter Ø$_{shoulder}$ = 20.0 mm and Ø$_{shoulder}$ = 25.0 mm;
- smooth conical pin with length Lpin=3.85mm; 5.0mm and 6.0mm; tool's smooth shoulder diameter Ø$_{shoulder}$ = 20.0 mm, the tool being built as one part made of sintered Wcarbide P20S;
- conical pin with four flat bevels, having length L_{pin} = 3.85 mm and 5.0 mm; tool's smooth shoulder, diameter Ø$_{shoulder}$ = 18.0 mm and 20.0 mm, the tool being built as one part made of sintered tungsten carbide P20S.

Rotational welding tool speed values of n = 750 rpm, 900 rpm and 950 rpm were used for friction stir butt welding, as well as n = 750 rpm, 900 rpm, 1150 rpm and 1200 rpm were used for overlap welding. Welding speeds had values in the range 20 mm/min -120 mm/min.

The experimental program for FSW butt welding of TiGr2 sheets (dimensions 200x100x4 mm), showed that using a welding tool with a cylindrical pin having length L_{pin} = 3.8 mm and tool's smooth shoulder diameter Ø$_{shoulder}$ = 25.0 mm, as well as the rotational welding tool speed n = 950 rpm and welding speed v = 95 mm/min, a welded joint without any visible defects is formed (Figure 2).

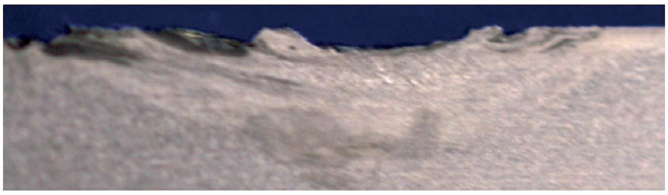


Figure 2. Macroscopic aspect of FSW butt welded joint, with smooth cylindrical pin

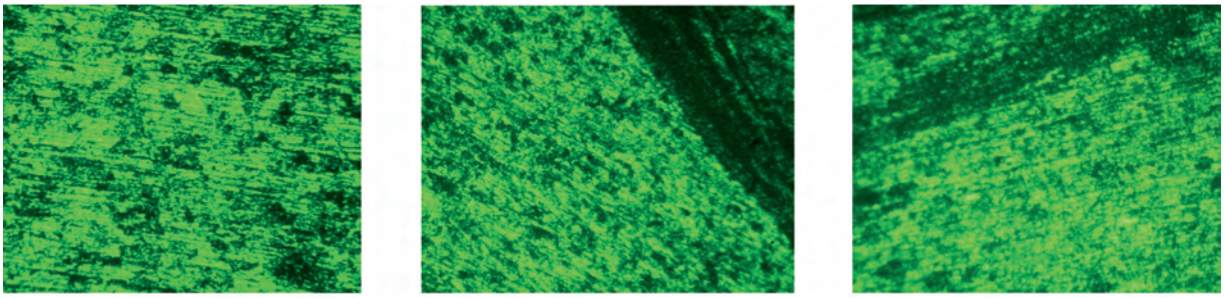
The microstructural analysis revealed the following more significant aspects (Figure 3):

- the base material (BM) has a α solid solution structure, with polyhedral grains having dimensions in the range of 60-80 µm;
- the heat affected zone (HAZ) on the advancing side (AS) and on the retreating side (RS) of the tool reveals a finer grain structure than that of the base material. On the retreating side of the tool, the grains are elongated, having a size of 5-67 µm, and on the advancing side of the tool, grains are polyhedral, with sizes varying between 12-46 µm;
- the thermomechanical heat affected zone (TMAZ), between the heat affected zone and the nugget area (N), does not indicate significant structural changes. However, it is emphasized that the solidification is preferentially oriented on the thermal flow direction, where the grains are more strongly deformed. These areas are in the form of separate flow strips, engaged in the concentrically motion, by the welding tool;
- in the nugget area (N), also a fine polyhedral grain is observed, while maintaining the granular solid structure αcharacteristic of the base material. Grain sizes vary between 2-7µm and the strong finishing of the nugget grains, compared to the BM and HAZ, can be observed.

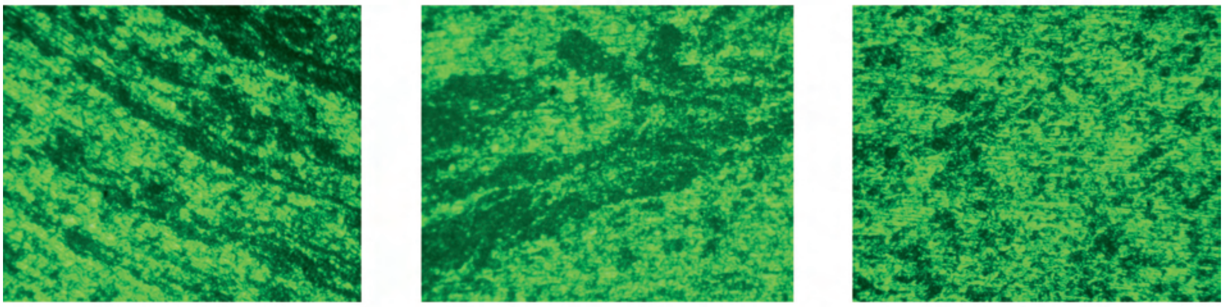
The temperature evolution during the welding process, monitored using infrared thermography, showed that the welding process became stable at approx. 900°C.

Microstructural and sclerometric analysis revealed the following aspects (Figure 4):

- the hardness of the BM is ~ 155-160 HV1;
- the maximum hardness values of 254-321 HV1 were recorded in the nugget, the higher values being recorded in the nugget area that corresponding to the AS of the welding tool;
- high hardness values, close to those recorded in the nugget, were also recorded in the TMAZ area;
- in the HAZ area, the hardness values are close to those of the base material.



BM-base material HAZ (RS of the tool) HAZ (AS of the tool)



TMAZ (RS of the tool) TMAZ (AS of the tool) Nugget - welded joint

Figure 3. Microstructure of the welded joint area – using the cylindrical pin tool

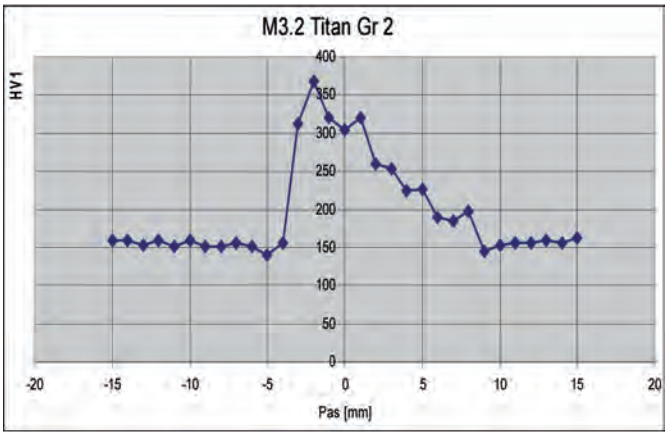


Figure 4. Variation of hardness in the welded joint

The hardness evolution reveals the existence of a strip of material with a hardening of approx. 33% between the HAZ and the N area, as a result of the plastic deformation to which the material was subjected (granulation finishing).

The results of the static tensile test indicated an average tensile strength of 398 N/mm^2, which represents 90.5% of the mechanical strength of TiGr2 as the base material.

The experimental FSW welding program by overlapping of TiGr2 titanium sheets having dimensions 200x100x4 mm showed that using a welding tool with conical pin having length L_{pin} = 5.0mm and smooth tool shoulder with diameter $Ø_{shoulder}$ = 20mm, the rotational welding tool speed n = 1150 rpm and welding speed v = 100 mm/min, a welded joint is formed without the appearance of imperfections (Figure 5). Welding process was performed using argon gas with a flow rate of 6 l/min.

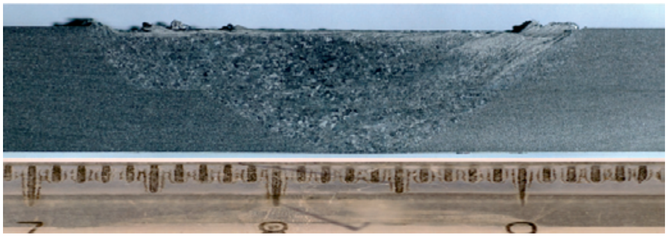


Figure 5. The macroscopic aspect of the welded joint

The sample from Figure 5 was taken after approximately 90 mm welding, when the welding process has been stabilized and the process temperature (recorded using infrared thermography) was 1400°C (Figure 6). It can be observed that the "mixed" material area which are forming the welded joint has been greatly expanded (up to the backing plate). The welding width in interference area between the titanium sheets is 7.5 mm, even though the base materials have been influenced by the action of the pin of the welding tool on a width of approx. 10.5 mm. No welding imperfections are observed.

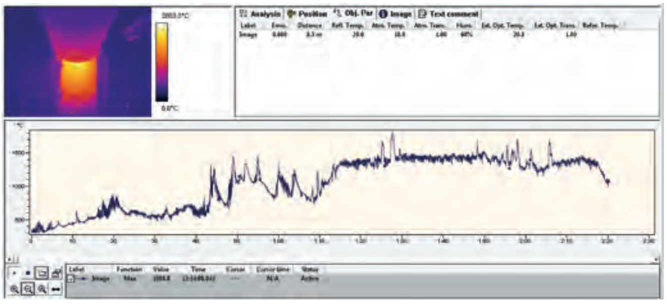


Figure 6. Evolution of the temperature during the welding process

Argon, as a protective gas, is used for the titanium welding to protect the welding area having as affect the improvement of the welded surface appearance, as well as reducing the wear of the welding tool. Figure 7 shows comparatively the welding of titanium TiGr2 without protective gas and with argon as protective gas, as well as the weld joint aspect in both cases.

At the titanium welding without protective gas, sparks occur during the welding process, the weld surface having a blue-gold tint color and a high roughness. The use of protective gas (argon) with a flow rate of approx. 6 l/min has contributed to the improvement of the quality and of appearance of the welded joint surface (color closer to that of the base material – ash gray) and to the considerable reduction of the roughness values, with approx. 80% (compared with welding without protective gas).

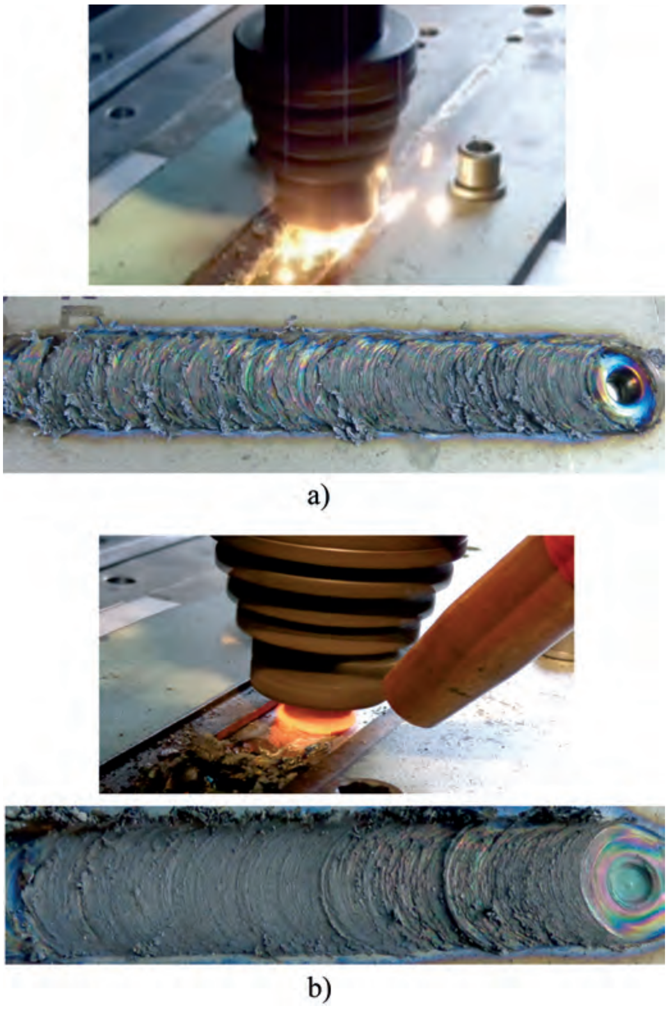


Figure 7. FSW welding of titanium TiGr2: a) without protective gas, b) with protective gas (Ar)

It is worth mentioning that in the case of the presented experiments, the argon was provided in the working area by using a tube connected directly to the gas tank, at a prescribed pressure.

Even though the technical way of ensuring the inert gas (argon) in the welding area was not the most efficient, the beneficial effects of FSW welding TiGr2 titanium in argon environment were found.

This fact has led the team of authors to propose researches in the framework of a research project (in progress), which aims to ensure optimal conditions for the application of FSW welding in the gas environment.

Figure 8 show a basic sketch of a device that will be adapted to the FSW machine from the ISIM Timisoara endowment (on the main shaft of the machine - Figure 9), which to allow efficient implementation of the FSW welding process in an inert gas environment.

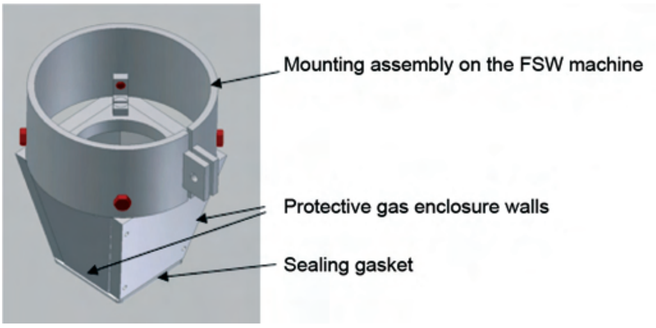


Figure 8. Sketch of a fixed device for the application of protective gas to FSW-IG

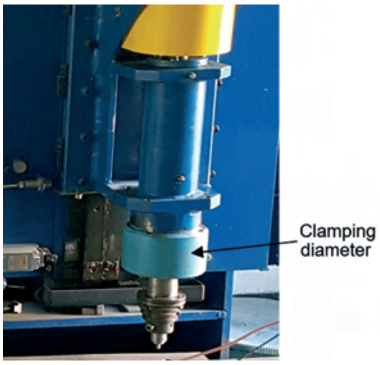


Figure 9. Main shaft of the FSW welding machine

Also, ISIM Timisoara is looking for solutions that could bring “a plus” from a qualitative point of view to titanium alloys welding, for example, the use of an FSW hybrid process ultrasonically assisted [96]. There are concerns about demonstrating the viability of this new process [97].

4. Conclusions

The FSW process can be applied to the butt and overlapping welding of TiGr2 titanium sheets.

The use of a smooth cylindrical pin to the FSW butt welding, lead to the best results for titanium joining, using a rotational tool speed of n = 950 rpm and a welding speed of v = 95mm/min. The use of a conical pin with four flat bevels and a smooth conical pin, to the FSW butt welding, may cause some of cavity type defects, incomplete penetration and tunnel type defects.

The use of smooth conical pin to the FSW welding by overlapping, has led to obtaining of good welding results. The conical pine with four planed bevels caused occurrence of the defects in the weld area.

In order to optimize the welding process, it is necessary to correlate all the factors that can influence the quality of the welded joint: the geometry and dimensions of the welding tool, the rotational tool speed, the welding speed, the penetration depth of the pin in the sheet placed below (in case of overlapped sheets), the pressing force of the tool’s shoulder on the materials to be joined, sense of rotation of the tool, use of protective gas, a.o.

The use of protective gas (argon) can contribute to improve the quality and aspect of the weld surface and to considerably reducing of roughness, by about 80% (compared with welding without protective gas).

Acknowledgements

The paper was elaborated on the basis of the results obtained within the project PN 19.36.01.01 entitled “Researches on the development of new innovative methods of application of the friction stir welding process in order to extend the application possibilities in priority areas” financed by the Ministry of Research and Innovation, in the frame of Nucleu Program of ISIM Timisoara (contract 35N / 2019).

References

[1]. R. Johnson, S. Kallee: ”Friction stir welding”, Materials World, Vol. 7, No. 12, p. 751 – 753, (1999);

[2]. AzoM Com.: “The selection and use of Titanium”, A Design Guide – Materials Information Service, The Institute of Materials, (2002);

[3]. P.M. Mashini: Process window for friction stir welding of 3mm titanium (Ti6Al-4V), research dissertation, Faculty of engineering, the built environment and information technology, Nelson Mandela Metropolitan University (2010);

[4]. Hong Liu, Kazuhiro Nakata, Naotsugu Yamamoto, Jinsun Liao: Grain orientation and texture evolution in pure titanium lap joint produced by friction stir welding, Material Transactions, Vol.51, No.11, pp. 2063 – 2068 (2010);

[5]. M.J. Russell, C. Blignault, N.L. Horrex, C.S.Wiesner: Recent developments in the friction stir welding of titanium alloys, Welding in the World, vol. 52 nr.9/10 (2008);

[6]. A. J. Ramirez and M. C. Juhas: Mater. Sci. Forum 426–432, 2999–3004 (2003);

[7]. W. B. Lee, C. Y. Lee, W. S. Chang, Y. M. Yeon and S. B. Jung: Mater. Lett. 59 3315–3318 (2005);

[8]. L. Zhou, H. J. Liu, P. Liu and Q. W. Liu: Scr. Mater. 61 596– 599 (2009);

[9]. Y. Zhang, Y. S. Sato, H. Kokawa, S. H. C. Park and S. Hirano: Mater. Sci. Eng. A 488, 25–30 (2008);

[10]. A. P. Reynolds, E. Hood and W. Tang: Scr. Mater. 52, 491–494 (2005);

[11]. S. Mironov, Y. S. Sato and H. Kokawa: Acta Mater. 57, 4519–4528 (2009);

[12]. H. Fujii, Y. Sun, H. Kato and K. Nakata: Mater. Sci. Eng. A 527,3386–3391 (2010);

[13]. K. Reshad Seighalani, Givi. M. K. Besharati, A. M. Nasiri and P.Bahemmat: J. Mater. Eng. Perform. 18, 1–8, (2009);

[14]. Zhang Yu, Sato YS, Kokawa H, Park SHC, Hirano S.: Microstructural characteristics and mechanical properties of Ti-6Al-4V friction stir welds. Material Science and Engineering A. (2008); 485(57):448-55;

[15]. D. G. Sanders, M. Ramulu, E. J. Klock-McCook, P. D. Edwards, A. P .Reynolds and T. Trapp: J. Mater. Eng. Perform. 17, 187–192, (2008);

[16]. J.-D. Kim, E.-G. Jin, S. Murugan, Y.-D. Park: Journal of Welding and Joining 35, 6-15 (2017);

[17]. N. Xu, Q. Song, Y. Bao, Y. Jiang, J. Shen, X. Cao: Science and Technology of Welding and Joining 22, 610-616 (2017);
[18]. M. Peters, J. Kumpfert, C.H. Ward, C. Leyens: Advanced Engineering Materials 5, 419 – 427 (2003);
[19]. H.-X Jin, K.-X Wei, J.-M Li, J.-Y Zhou, W.-J. Peng: Zhongguo Youse Jinshu Xuebao/Chinese Journal of Nonferrous Metals 25, 280-292 (2015);
[20]. E. Uhlmann, R. Kersting, T. Klein, & M. Fernando Cruz, A. Borille: Procedia CIRP 35, 55-60 (2015);
[21]. M.J. Russell.: Friction Stir Welding of Ti Alloys – A Progress Update, Ti-2003, 10th World Conference on Titanium, Hamburg, Germany, (2003);
[22]. D. Hass: “Titanium – You can weld it !”, The Fabricator publication, April (2004);
[23]. Zhang Yu, Sato YS, Kokawa H, Park SHC, Hirano S.: Microstructural characteristics and mechanical properties of Ti-6Al-4V friction stir welds. Material Science and Engineering A. (2008); 485(57):448-55;
[24]. C.B. Fuller: Friction Stir Tooling: Tool Materials and Designs, Friction Stir Welding and Processing, pag.7-37, ASM International (2007);
[25]. R.S. Mishra, M.W. Mahoney: Friction stir welding and processing. ASM International, (2007) March 30;
[26]. P.M. Mashini: Process window for friction stir welding of 3mm titanium (Ti6Al-4V), research dissertation, Faculty of engineering, the built environment and information technology, Nelson Mandela Metropolitan University (2010) ;
[27]. M.J. Russell: Friction stir welding of titanium alloys – a progress update. 10th World Conference on Titanium, Hamburg. (2003) July 13-18;
[28]. M. Ikeda, S. Hasegawa, C.S. Wook, K. Higashi: Fundamental study for development of new tool for titanium and its alloys, 6th International Symposium on Friction Stir Welding, Montreal, Canada.(2006), October 10-12;
[29]. S. Mironov, Y. Zhang, Y.S. Sato, H. Kokawa: Development of grain structure in b-phase field during friction stir welding of Ti-6Al-4V alloy. Scripta Materialia. (2008); 59(9):27-30;
[30]. Z. Loftus, J. Takeshita: An overview of friction stir welding TIMETAL 21S beta titanium. 5th International Friction Stir Welding Symposium, Metz, France. (2004) September 14-16;
[31]. W.B. Lee, C.Y. Lee, W.S. Chang, Y.M. Yeon, S.B. Jung: Microstructural investigation of friction stir welded pure titanium. Material Letters. (2005); 59(29):3315-18;
[32]. R.S. Mishra, M.W. Mahoney: Friction stir welding and processing. ASM International. (2007) March 30;
[33]. B. Li, Y. Shen, L. Luo, W. Hu: Sci. Eng. A 574 (2013) 75-85;
[34]. Z. Ding, C.J. Zhang, L. Xie, L.-C. Zhang, L.Wang, W. Lu: Metall. Mater. Trans. A47A(2016) 5675-5679;
[35]. B. Li, Y. Shen, L. Luo, W. Hu, Z. Zhang: Mater. Des. 49 (2013) 647-656;
[36]. K. Kitamura, H. Fujii, Y. Iwata, Y.S. Sun, Y. Morisada: Mater. Des. 46 (2013)348-354;
[37]. S. Yoon, R. Ueji, H. Fujii: Mater. Charact. 106 (2015) 352-358;
[38]. L. Fratini, F. Micari, G. Buffa, V.F. Ruisi: CIRP Ann. - Manuf. Technol. 59 (2010)271-274;
[39]. J. Wang, J. Su, R.S. Mishra, R. Xu, J.A. Baumann: Wear 321 (2014) 25-32;
[40]. B. Li, Y. Shen, W. Hu, L. Luo: Surf. Coat. Technol. 239 (2014) 160-170;
[41]. L. Zhou, H.J. Liu, P. Liu, Q.W. Liu: Scripta Mater. 61 (2009) 596-599;
[42]. H.J. Liu, L. Zhou, Q.W. Liu: Scripta Mater. 61 (2009) 1008-1011;
[43]. A.L. Pilchak, M.C. Juhas, J.C. Williams: Metall. Mater. Trans. A 38 (2007)401-408;
[44]. S. Ji, Z. Li, L. Zhang, Y. Wang: Mater. Lett. 188 (2017) 21-24;
[45]. L. Zhou, H.J. Liu, Q.W. Liu: Mater. Des. 31 (2010) 2631-2636;
[46]. H.J. Liu, L. Zhou, Q.W. Liu: Mater. Des. 31 (2010) 1650-1655;
[47]. S. Ji, Z. Li, Y. Wang, L. Ma: Mater. Des. 113 (2017) 37-46;
[48]. L. Zhou, H.J. Liu: Mater. Charact. 62 (2011) 1036-1041;
[49]. L. Zhou, H.J. Liu: Int. J. Hydr. Energy 35 (2010) 8733-8741;
[50]. H.J. Liu, L. Zhou: Trans. Nonferrous. Met. Soc. China 20 (2010) 1873-1878;
[51]. L. Zhou, H.J. Liu, L.Z. Wu: Trans. Nonferrous Met. Soc. China 24 (2014)368-372;
[52]. A.L.Pilchak, W. Tang, H. Sahiner, A.P. Reynolds, J.C. Williams: Metall. Mater.Trans. A 42A (2011) 745-762;
[53]. H. Farnoush, A.A. Bastami, A. Sadeghi, J.A. Mohandesi, F. Moztarzadeh, J. Mech: Behav. Biomed. Mater. 20 (2013) 90-97;
[54]. A.Farias, G.F.Batalha, E.F. Prados, R. Magnabosco, S.Delijaicov: Wear302(2013) 1327-1333;
[55]. B. Li, Y. Shen, W. Hu, Appl. Surf. Sci. 274 (2013) 356-364;
[56]. J. Wang, J. Su, R.S. Mishra, R. Xu, J.A. Baumann: Wear 302(2013) 1327-1333;
[57]. A.R. Nasresfahani, A.R. Soltanipur, K. Farmanesh, A. Ghasemi: Mater. Sci.Technol. 33 (2017) 583-591;
[58]. A. Khodabandeh, M. Jahazi: Metals 6 (2016)275;
[59]. L.H. Wu, B.L. Xiao, D.R. Ni, Z.Y. Ma, X.H. Li, M.J. Fu, Y.S. Zeng: Scripta Mater. 98(2015) 44-47;
[60]. L.H. Wu, P. Xue, B.L. Xiao, Z.Y. Ma: Scripta Mater. 122 (2016) 26-30;
[61]. G. Buffa, A. Ducato, L. Fratini: Mater. Sci. Eng. A 581 (2013) 56-65;
[62]. A.L. Pilchak, D.M. Norfleet, M.C. Juhas, J.C. Williams: Wear 302(2013) 1327-1333;
[63]. A.L. Pilchak, J.C. Williams: Metall. Mater. Trans. A 42A (2011) 1630-1645;
[64]. M. Esmaily, S.N. Mortazavi, P. Todehfalah, M. Rashidi: Mater. Des. 47 (2013)143-150;
[65]. S. Pasta, A.P. Reynolds: Strain 44 (2008) 147-152;
[66]. S. Pasta, A.P. Reynolds: Fatigue Fract. Eng. Mater. Struct. 31 (2008) 569-580;
[67]. M. Atapour, A. Pilchak, G.S. Frankel, J.C. Williams: Corros. Sci. 52 (2010)3062-3069;
[68]. A. Lauro: Weld. Int. 26 (2012) 8-21;
[69]. G. Buffa, L. Fratini, M. Schneider, M. Merklein, J. Mater: Wear 302(2013) 1327-1333;
[70]. J. Su, J. Wang, R.S. Mishra, R. Xu, J.A. Baumann: Mater. Sci. Eng. A 573 (2013)67-74;
[71]. J.C. Lippold, J.J. Livingston: Metall. Mater. Trans. A 44 (2013) 3815-3825;
[72]. P. Edwards, M. Ramulu, J. Eng.: Mater. Technol. 132 (2010) 031006-031016;
[73]. A. Steuwer, D.G. Hattingh, M.N. James, U. Singh, T. Buslaps: Sci. Technol. Weld.Join. 17 (2012) 525-533;
[74]. P. Edwards, M. Ramulu: Sci. Technol. Weld. Join. 15 (2010) 468-472;

[75]. P. Edwards, M. Ramulu: Sci. Technol. Weld. Join. 14 (2009) 669-680;

[76]. P.D. Edwards, M. Ramulu, J. Mater: Proc. Technol. 218 (2015) 107-115;

[77]. P. Edwards, M. Ramulu, J. Mater: Eng. Perform. 24 (2015) 3263-3270;

[78]. P. Edwards, M. Ramulu: Fatig. Fract. Eng. Mater. Struct. 38 (2015) 970-982;

[79]. P.D. Edwards, M. Ramulu: Fatigigue Fract. Eng. Mater. Struct. 39 (2016)1226-1240;

[80]. M. Muzvidziwa, M. Okazaki, K. Suzuki, S. Hirano: Mater. Sci. Eng. A 652 (2016)59-68;

[81]. S. Yoon, R. Ueji, H. Fujii: Mater. Des. 88 (2015) 1269-1276;

[82]. S. Yoon, R. Ueji, H. Fujii, J. Mater: Process. Technol. 229 (2016) 390-397;

[83]. Y.S. Sato, S. Susukida, H. Kokawa, T. Omori, K. Ishida, S. Imano, S.H.C. Park, I.Sugimoto, S. Hirano: Proceedings of 11th International Symposium on FrictionStir Welding, Cambridge, UK, (2016), CD-ROM;

[84]. S. Mironov, Y. Zhang, Y.S. Sato, H. Kokawa: Scripta Mater. 59 (2008) 511-514;

[85]. S. Mironov, Y. Zhang, Y.S. Sato, H. Kokawa: Scripta Mater. 59 (2008) 27-30;

[86]. Y.Zhang, Y.S.Sato, H.Kokawa, S.H.C.Park, S. Hirano: Mater. Sci. Eng. A485(2008) 448-455;

[87]. T. Nakazawa, K. Tanaka, K. Sakairi, Y.S. Sato, H. Kokawa, T. Omori, K. Ishida, S.Hirano: Proceedings of 11th International Symposium on Friction StirWelding, Cambridge, UK, (2016), CD-ROM;

[88]. G. Buffa, L. Fratini, F. Micari, L. Settineri: Transactions of the North American Manufacturing Research Institution of SME 40, 785-794 (2012);

[89]. Y. Zhang, Y. S. Sato, H. Kokawa, C. P. Hwan Seung. S. Hirano: Materials Science and Engineering: A 488, 25-30 (2008);

[90]. U. Sobczak, M. Wachowski, L. Śnieżek, M. Bajkowski, K. Gocman: Machine Dynamics Research 41, 53-64 (2018);

[91]. R. Kosturek, M. Wachowski, T. Slezak, T. Sniezek, J. Mierzynski, U. Sobczak: Research on the friction stir wleding of Titanium Grade 1, MATEC Web of Conferences 242, 01006, (2018) https://doi.org/10.1051/matecconf/201824201006 CAFMC2018;

[92]. G. Buffa, L.Fratini, F. Micari: On the choice of tool material in friction stir welding of titanium alloys, Proceedings of NAMRI/SME, vol.40, (2012);

[93]. L.H. Wu, D. Wang, B.L. Xiao, Z.Y. Ma: Mater. Chem. Phys. 146 (2014) 512-522;

[94]. A. Fall, Mostafa H. Fesharaki, A.R. Khodabandeh, M. Jahazi: Metals 6 (2016)275;

[95]. I.M. Norris, W.M. Thomas, J. Martin, D.J. Staines: Friction stir welding – process variants and recent industrial developments. 10th International Aachen Welding Conference, „Welding and Joining, Key Technologies for the Future, Eurogress, Aachen. (2007) October 24-25;

[96]. O.V. Oancă, N.A. Sîrbu, E.F. Binchiciu, G.V. Mnerie, I.A. Perianu: Method and technologies functional constructive configuration concept of a flexible unconventional hybrid FSW-US welding process, The 9th International Conference "Innovative technologies for joining advanced materials", TIMA 18, 1 - 2 November 2018, Timisoara, Romania;

[97]. O.V. Oancă, G.V. Mnerie, E.F. Binchiciu, R. Cojocaru, L.N. Boțilă, I. Duma: Research on the welding for alloy EN AW 5754 when using FSW-US hybrid process, The 9th International Conference "Innovative technologies for joining advanced materials", TIMA 18, 1 - 2 November 2018, Timisoara, Romania.