Analysis of welding of aluminium alloy AA6082-T6 by TIG, MIG and FSW processes from technological and economic aspect

Aleksandra Koprivica, Darko Bajić, Nikola Šibalić, Milan Vukčević
Faculty of Mechanical Engineering - University of Montenegro
E-mail: aleksandra.koprivica@fpm.ues.rs.ba, darko@ucg.ac.me, nikola@ucg.ac.me, milanvu@ucg.ac.me

Abstract: *Welding is a manufacturing process, which uses heat or pressure to form a homogeneous weld when joining homogeneous or heterogeneous metal materials or thermoplastics. The last decade has been characterized by the intensive development of unconventional welding processes, which use friction as an energy source, and in developed countries have taken primacy over conventional welding processes. The modern welding process, known as Friction Stir Welding (FSW), offers many advantages over conventional Tungsten Inert Gas (TIG) and Metal Inert Gas (MIG) processes, both in terms of weld quality and environmental protection and in terms of saving time and materials needed to perform quality welding. This paper presents TIG, MIG and FSW welding technologies, with all the advantages and disadvantages, and the possibilities of their application in welding AA6082-T6 aluminum alloy (6xxx series), characterized by medium strength and outstanding corrosion resistance.*
Keywords: *WELDING, TIG, MIG, FSW, COST*

1. Introduction

Welding is a technological process that has a wide range of applications in the manufacture of metal products in the mechanical, automotive, aviation, construction and energy industries. During the period after the First World War, there was an intensive development of welding, so during that time portable welding machines were developed in the protective atmosphere of inert and active gas.

Nowadays, welding technology is at a highly advanced level, which makes it possible to use it in all conditions - in space, underwater, at high altitudes, etc., and precision machines have been constructed, which perform defined operations with lasers. Conventional welding processes, in developed industrial countries, are being replaced by new, unconventional ones, including Friction Stir Welding (FSW) or friction welding, patented in 1991 by The Welding Institute (TWI) in England. Originally, this welding process was intended solely for welding aluminum and its alloys [1].

FSW technology, in addition to its original use in aluminum welding, is now successfully used in welding copper, brass and various types of steel. In addition, the orbital variant of the FSW process is used for welding metal and plastic tubes, the spot welding is used in the automotive industry, and for complex shapes and contours, a robotic FSW procedure is in use [1].

The advantages of the FSW welding process over conventional technologies, primarily TIG and MIG, have been explained in the work of a number of researchers [2- 4]. The peculiarity of this process is reflected in the time and cost required to perform welding, and in the protection of health and the environment, as well as safety at work.

This paper analyzes the welding of aluminum alloy 6xxx series (AA6082-T6) from the aspect of three technological processes, namely two melting welding processes (TIG and MIG) and one non-melting process (FSW).

Welding aluminum is difficult for many reasons. Aluminum has a high thermal conductivity, a low melting point relative to the oxide layer, and an affinity for oxygen and hydrogen, which makes it difficult to weld.

Based on research based on a large number of literature sources, this paper wanted to point out the possibility of applying certain methods for welding aluminum, namely its alloy AA6082-T6.

2. Conventional welding processes

2.1. Tungsten Inert Gas (TIG)

TIG Technology, or Wolfram Inert Gas (WIG), or Gas Tungsten Arc Welding (GTAW) is arc welding with insoluble electrode in the protection of inert gas (argon, helium) or less often in a mixture of gases dominated by inert gas, whose original use binders for welding aluminum and its alloys thanks to the effect of cathodic cleaning [1, 5, 6].

Due to a number of advantages, this process is of use in welding a wide range of materials (steels, precious steels, heavy and light non-ferrous metals, etc.) in manual, semi-automatic or automatic applications. It found application in the automotive and aviation industries, shipbuilding, production of transportation systems, various overhaul works, etc. The obtained compounds of high quality are the reason that the TIG process is currently irreplaceable in the design and installation of pipelines, boiler, petrochemical industry, etc. Good process mobility allows it to be applied in all spatial positions. Nowadays, characterized by a high degree of automation and application of modern technologies, the field of application of the TIG process is significantly expanded.

The main advantages of the TIG procedure are [5, 6]:

- high quality joint - faultless joint,
- no spattering - additional metal melts in the metal bath, does not transfer through the arc,
- excellent weld root control,
- precise control of welding parameters,
- good control of the heat source and the way of introducing additional material,
- no submerging,
- a large number of welding positions and
- possibility of welding of dissimilar metals.

In addition to a number of advantages, which are more dominant, the TIG process has its disadvantages, such as:

- relatively low welding speed and productivity,
- requires a high level of training of welders,
- inert gases are expensive, increasing the total cost of welding,
- in addition to the occurrence of defects in the weld due to inadequate welding techniques, as a result of the electrode overheating, tungsten particles may be introduced into the weld, thus reducing the quality of the weld,
- high cost of equipment and
- increase UV radiation.

2.2. Metal Inert Gas (MIG)

The MIG welding process represents arc welding with a full soluble wire electrode in the protection of inert gas or gas mixtures with a predominant argon or helium content.

This procedure is applicable for welding material 3-20 mm thick. In addition, pulsed MIG transmission is used for welding thin materials 1-4 mm thick, as well as for welding in forced positions [1].

The basic components that affect the electric arc that is created and therefore the metal transfer in the weld zone and the quality of the weld are the forces and chemical reactions that occur in the metal transfer area. The forces that occur and act in the zone of an arc are: electromagnetic force, gravity force, surface tension force of liquid metal, reaction force from the flow of steam from the surface of the melt and aerodynamic force [1].

The advantages of the MIG welding process are:

- high melting rate and high welding speed,
- applicable in forced positions,
- small investment costs (for the standard variant),
- excellent appearance of welded joints and
- easy process automation [6].

The disadvantages of the MIG welding process are:

- risk of welding errors,
- the risk of slow welding errors due to the leakage of liquid metal in front of the electric arc and
- relatively complicated welding training for high alloy steels and non-ferrous metals [6].

3. *Friction stir welding (FSW)*

In addition to aluminum and aluminum alloys, FSW is nowadays successfully used for welding bronzes, brass, as well as some types of steel. In addition, the orbital variant of the FSW procedure is used for welding metal and plastic tubes, the spot welding is applied in the car industry, and for complex shapes and contours, a robotic FSW procedure is in use [1].

The FSW procedure is performed in such a way that there are firmly clamped base plates on the machine table that need to be connected. A special cylindrical shape tool, consisting of two parts, the body and the working part of the tool, which rotate at high speed, is used to generate heat. The tool body is used to attach the tool to the clamping jaws of the machine, and the working part of the tool consists of two parts: a larger diameter called the shoulder and a smaller diameter part called the pin (Figure 1) [7].

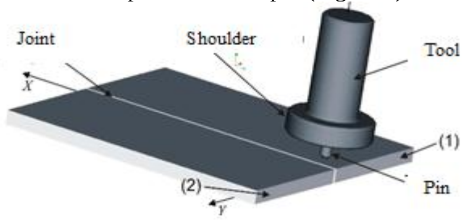


Figure 1. *Tool and work pieces before welding [8]*

The shape of the shoulder and the pin of the tool can have different structural geometric shapes. The shoulder of tool may have a concentric recess in its surface of usually semicircular shape, while the pin is usually conical, which can also be profiled by different coil shapes or different types of grooves. The height of the grooves mainly depends on the thickness of the welding (joining) sheets, but it is very important that it be a few millimeters smaller than the thickness of the sheet [8].

The FSW process starts with the positioning of the tool above the workbench of the machine, and its axis is normal to the touching line of the base plates. The rotary tool approaches the joint line slightly and plunges into the material - the base plates. On this occasion, heat is generated in the material and an initial hole is formed. The tool pin is plunged in the material until the tool face makes contact with the upper surface of the work pieces. The tool must with sufficient pressure hold the material within the weld zone and create a sufficient temperature for the FSW process to proceed smoothly [8]. The baseplate material is heated to near the melting point (~ 95%) and becomes plastic. With the help of a pin tool, such material flows around the sleeve and thus mixes. At the moment when the tool head touches the upper surfaces of the base plates, the axial movement of the tool is interrupted and the longitudinal movement of the stand begins. In further work, the tool pin practically slides between the sheets in the welding direction, the new material warms up, becomes plastic and is constantly mixed. During this time, a groove of smooth warmed material is formed behind the tool head, which cools and solidifies, and a monolithic joint is formed between the plates. In doing so, the tool face forms a flat seam surface on the top of the sheet, and on the underside, the base forms the same. The welding process is terminated by interrupting the translational movement of the tool and pulling it out of the weld zone axially upwards [8].

The thickness of the aluminum sheet that can be welded by this method depends on the strength of the machine and ranges from 0.5 mm to 50 mm in a single pass or single sided seam. It is possible to weld sheets up to 75 mm thick in double sided seam.

As the nature of FSW is a solid state, this gives it several advantages over metal melting welding methods: liquid phase cooling is avoided so that porosity (cavity), solution redistribution, and cracks formed by melting and solidification do not exist.

In principle, the FSW process has found great application. There are a number of disadvantages and as a process it is very tolerant in terms of variation of parameters and materials. One of the significant advantages over arc welding processes is that there is no distortion, ie. of sheet metal bending during the process itself, because the residual stresses are negligibly small.

In addition to the above, the FSW process has properties that are very rarely present in other processes: the formation of a welded joint with negligible internal stresses, resistant to corrosion, in materials for which this was not possible or extremely difficult and expensive to achieve by conventional methods welding. Due to all of the above, it can be said that, economically, FSW process is by far the most efficient and ecologically clean [8].

4. *Aluminium alloy AA6082-T6*

Aluminum and its alloys, as structural materials, characterized by good mechanical properties, corrosion resistance and relatively low mass, today occupy a significant place in almost all branches of industry. The most common use of aluminum alloy is in the shipbuilding, aerospace, aerospace, healthcare, construction, and other industries [9, 10].

Welding of aluminum and aluminum alloys is accompanied by certain technical problems that can be avoided by properly selecting the welding process and the additional material [9]. Aluminum oxide formed on the surface of the metal provides corrosion resistance, so subsequent surface protection is basically unnecessary. If the coating is removed, in contact with oxygen from the air it regenerates at that point. As *Al* oxide has a melting point of about 2050 ºC and aluminum of about 660 ºC, in the welding preparation process, this oxide must be removed mechanically from the junction site.

A special type of aluminum alloy from the 6xxx series (magnesium and silicon alloying elements), of which considerable attention will be paid in the next part, is the AA6082-T6 alloy. The T6 designation itself indicates that the AA6082 alloy has been further processed (T6 - heat treated in 580 ˚C and aged artificially at 180 ºC, tensile strength of 340 MPa, 95 HB hardness and specific mass) to improve mechanical properties [11-13]. The alloy is a medium strength alloy with a high degree of corrosion resistance. If the whole 6xxx series is considered, then this alloy has the highest strength, so it is not infrequently used as a replacement for some alloys in this series, especially for the construction of high load structures and the like [12].

The chemical composition of AA6082-T6 alloy is shown in Table 1 [7].

Table 1. *Chemical composition of AA6082-T6 alloy*

Al %	Fe %	Si %	Ti %	Cu %	Zn %	V %	Cr %	Mn %	Mg %	Na %
98.25	0.22	0.85	0.01	0.002	0.062	0.006	0.001	0.16	0.43	0.002

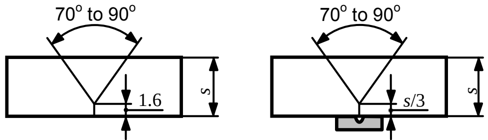
5. *Comparison of welding of AA6082-T6 alloy from the aspect of manufactura-bility by TIG, MIG and FSW processes*

In the next part of this paper, attention will be paid to the welding technology of said alloy, TIG, MIG and FSW processes, and an advanced analysis of these procedures will be made. Comparisons between the selected procedures to be analyzed are: time and cost of preparation of welding joint, cost of additional material, cost of protective atmosphere, energy consumption during welding, welding time and possible spatial positions of welding.

The comparison was considered when welding the face joint of the plates, AA6082-T6 alloy, length 1 m and thickness 6 mm. The consideration will take into account that the panels have been adequately machined to a defined length and width, and the time and cost of these panel preparations will not be taken into account.

5.1. Time and cost of preparing the weld joint

A special feature and problem in welding aluminum and its alloys is the oxide layer (Al_2O_3), which is constantly formed on the surface of the alloy and its high melting point relative to the low aluminum melting temperature. Aluminum oxide represents a basic difficulty that must be overcome in the arc welding of aluminum and aluminum alloys [14, 15], so it is necessary to remove the oxide layer from the base material. In the case of arc jointing of the material, especially in the formation of an interface, the groove side. The preparation of the groove sides of the TIG and MIG procedures for the AA6082-T6 aluminum alloy, s = 6 mm thick, is shown in Figure 2.



a) *b)*

Figure 2. *Preparation of weld seams: a) with TIG procedure for material of thickness 6 mm; b) in the MIG process for a material thickness of ≈6 mm [16]*

Considering that the cutting of the edges is performed by a spindle milling machine, and that the time required to perform this operation is calculated by the form:

$$t_t = t_p + t_m \qquad (1)$$

where are:

t_t - total time (min) required to cut the edge,

t_p - preparation time, which refers to the preparation of the machine, tools, positioning of objects, program entry and the like, and is about 30-40 min,

t_m - main process time (min).

According to the calculation, the time required for the preparation of the arc welding plates is 50-60 min, and the cost of preparing them is approximately 20 €.

In addition to the above costs, unlike the MIG process, the costs associated with preheating the material prior to the welding process must be added to the TIG process. In this regard, the preparation time for the TIG process is significantly higher than for the MIG process, because the heating of the AA6082-T6 alloy is performed at 200 ˚C for 30 min [17].

Unlike the aforementioned procedures, in the FSW process, the numerous costs of preparing the material are minimized, to be exact, almost nonexistent. In this process it is not necessary to preheat the material or to remove the protective oxide layer from the alloy surface in order to perform this process.

The time and cost required to prepare the material are shown in the diagrams in Figure 3 and Figure 4.

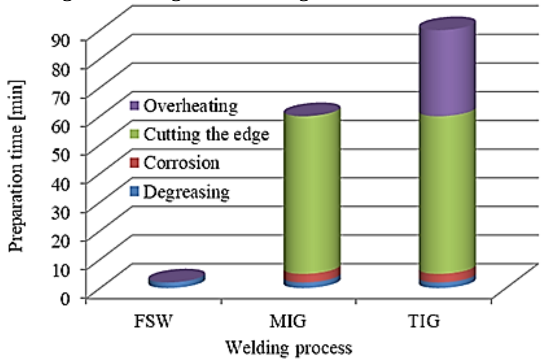


Figure 3. *Preparation time of material AA6082-T6 of thickness 6 mm for FSW, MIG and TIG welding*

5.2. Cost of additional material

Material that is added or introduced into the welding zone during the welding process and which together with the base material participates in the formation of the weld is called additional material. In general, 6xxx series alloys are not recommended to be welded without additional material, or to use additional material the same as the base material as cracking may occur in the weld [18].

Performing the TIG procedure is possible with or without additional material, that is, if the thickness of the base material is less than 3 mm, additional material is not required, otherwise it is necessary [5].

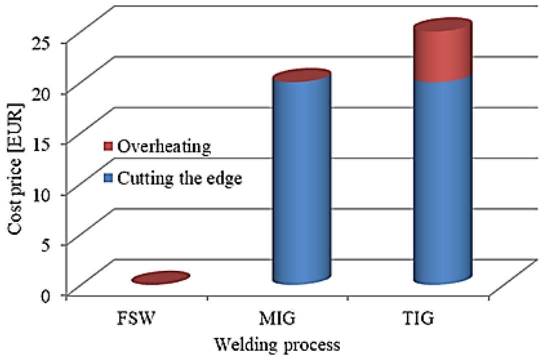


Figure 4. *Costs of material preparation AA6082-T6 of thickness 6 mm for FSW, MIG and TIG welding*

According to the literature source [19], additional material ER4043 is used when welding the AA6082-T6 TIG alloy process.

The speed of introduction of the auxiliary material and its diameter should be consistent with the welding speed and represent one of the main welding parameters, and are selected based on the thickness and type of the base material, as well as the welding position [9].

It is important to note that during the FSW welding process, no additional material is introduced into the process, the welding is performed without additional material.

Based on the recommendation of literature sources [20-23], the consumption of additional material for welding 1 m of AA6082-T6 of thickness 6 mm alloy was calculated and the calculated values are shown in the diagram in Figure 5.

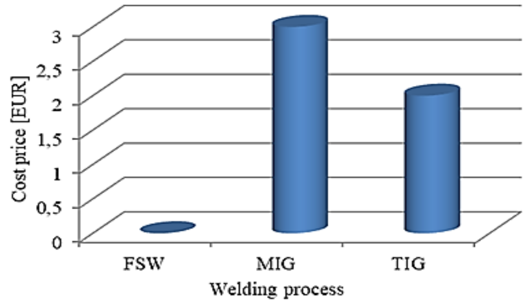


Figure 5. *Costs of additional material required for welding AA6082-T6 of thickness 6 mm FSW, MIG and TIG*

5.3. Time of welding

Welding time is another of the technological parameters when comparing TIG, MIG and FSW procedures.

When calculating the welding time, it is necessary to pay attention to the number of passes required to obtain the weld, and in this connection TIG and MIG welding of AA6082-T6 alloy of thickness 6 mm is performed in two, while FSW welding is performed in one pass.

Considering the researches [20, 22, 24], the time required for welding of AA6082-T6 alloy plates, length 1 m and of thickness 6 mm, by TIG, MIG and FSW procedures was calculated and is shown in the diagram in Figure 6, while the total time required to perform of these procedures is illustrated by the diagram in Figure 7.

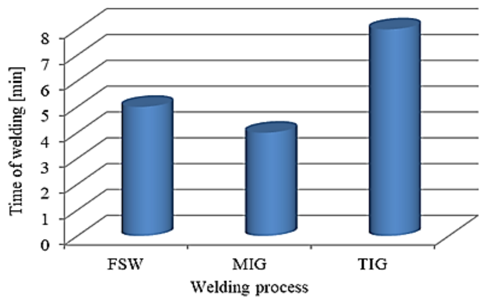


Figure 6. *Time for welding by TIG, MIG and FSW processes*

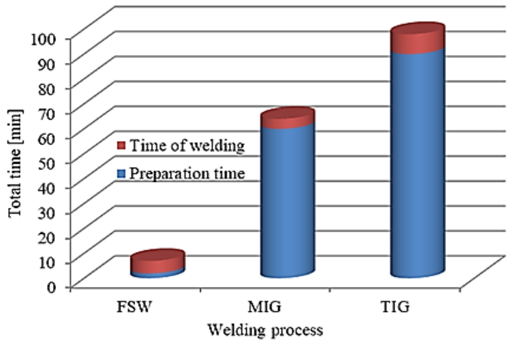


Figure 7. *Total time of extraction FSW, MIG and TIG processes*

5.4. Cost of a protective atmosphere

The cost of a protective atmosphere is another indication of the advantages of the FSW procedure over the TIG and MIG procedures. In fact, FSW welding does not require a protective atmosphere, while in TIG and MIG procedures it is necessary.

Based on the research [20, 22, 25], the argon consumption during welding of AA6082-T6 alloy, 1 m and of thickness 6 mm in length, was calculated by TIG and MIG procedures and presented, together with other costs, in Figure 8.

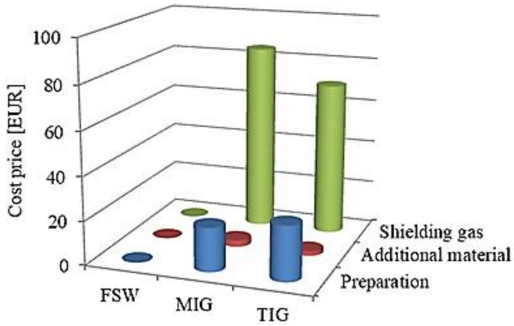


Figure 8. *Individual costs of welding processes*

5.5. Amount of heat input

A factor that greatly influences the shape and dimensions of weld metal and welds as a whole, the micro and macrostructure of weld metal and its properties, the occurrence of defects in the welded joint and the appearance of residual stresses is the energy that is brought under the influence of an electric arc welded joint [26].

The amount of energy input is a fraction of the total energy of the arc that is spent on forming a unit of length of weld. The amount of energy input is determined from the expression [26]:

$$Q = \frac{k \cdot U \cdot I}{v} \ \text{(J/m)} \qquad (2)$$

where are:

k - coefficient of thermal efficiency (for TIG - 0.6, and for MIG - 0.8),

U - voltage (V),

I - amperage (A) and

v - welding speed (m/s).

Unlike the TIG and MIG procedures, in the FSW process, the amount of energy input cannot be calculated using the form provided. However, based on data from a literature source [27], related to the amount of energy input in the FSW process, and based on the calculation by equation (2) for the TIG and MIG procedures, the amount of energy input for the individual welding operations is shown in the diagram in Figure 9.

6. Conclusion

Considering the time aspect of the overall process execution, including the time required to prepare the base material for welding and welding time, the FSW process takes precedence. In fact, in this process, preparation of the material is not required, while in the other two processes it is necessary, especially in the TIG process, which in addition to mechanical preparation of the material also requires its preheating. Therefore, the longest time is required for TIG welding and the shortest time for FSW welding.

However, if an economic analysis of the process, which includes material preparation costs, additional material costs and protective gas costs, is taken into account, FSW procedure is again preferred because material preparation costs are not present, no additional material is required, as well as protective gas. Most costs occur with MIG welding due to the high consumption of shielding gas.

Comparing the values related to the total amount of heat input during welding, it is concluded that from the energy point of view, FSW is a cost-effective procedure and is favored over the other two processes.

In addition to all of the above, today, which is characterized by high levels of pollution, great attention should be paid to the protection of the environment. From this point of view, the FSW process is one of the environmental practices because there is no evaporation of harmful gases, no protective gas required, high energy savings, etc.

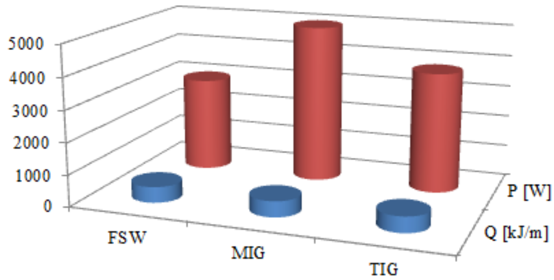


Figure 9. *Quantity of heat input and power consumption*

Literature

1. Bajić D., *Postupci zavarivanja*, Univerzitet Crne Gore, Mašinski fakulte, Podgorica, 2014.
2. Gopi S., Manonmani K., *Study of friction stir welding parameters in conventional milling machine for 6082-T6 aluminium alloy,* Australian Journal of Mechanical Engineering, Vol 10 No 2, pp. 129 – 140, Institution of Engineers Australia, 2012.
3. Singha G., Kanga S. A., Singhb K., Singhb J., *Experimental comparison of friction stir welding process and TIG welding process for 6082-T6 Aluminium alloy*, Materials Today: Proceedings 4. pp. 3590–3600, 5th International Conference of Materials Processing and Characterization (ICMPC 2016).
4. Veljić D., Sedmak A., Rakin M., Radović N., Popović N., Daşçău H., Bajić N., *Prednosti zavarivanja trenjem sa miješanjem u odnosu na elektrolučno zavarivanje – zaštita zdravlja i životne sredine i bezbednosti na radu*, Integritet i vek konstrukcija, Vol. 15, br. 2 (2015), str. 111–116, 2015.
5. Horvat M., Kondić V., Brezovečki D., *Teorijske i praktične osnove TIG postupka zavarivanja*, Technical Journal 8, 4(2014), ISSN 1846-6168, str. 426 - 432.
6. Milotić M., *Priručnik za zavarivače*, 2. Dopunjeno izdanje, Saobraćajni fakultet Doboj, 2008.
7. Šibalić N., Vukčević M., *Research on the Quality of the Welded Joint of Aluminium Alloy Sheet AA6082-T6 Using FSW, MIG and,* Materials and technology, 53 (5), 711–715 2019.
   doi:10.17222/mit.2018.224
8. Šibalić N., Vukčević M., Janjić M., Savićević S., *A study on Friction Stir Welding of AlSi1MgSn aluminium alloy plates*, Tehnički vijesnik, 3(2016), ISSN 1330-3651, pp. 653-660, 2016.
9. Wemen K., Lindén G., *MIG Welding Guide*, Woodhead Publishing and Maney Publishing on behalf of The Institute of Materials, Minerals & Mining, Cambridge of Endgland, 2005.
10. Vručinić G., *Zavarivanje i zavarljivost aluminija i legura*, 5.

SEMINAR Aluminij i aluminijske legure – rukovanje, priprema, zavarivanje, Pula, 2008.
11. Gopi S., Manonmani K., *Study of friction stir welding parameters in conventional milling machine for 6082-T6 aluminium alloy*, Australian Journal of Mechanical Engineering, Vol 10 No 2, pp. 129 – 140, Institution of Engineers Australia, 2012.
12. Jakobsen J. V., *Project*: *Microstructure and Mechanical Properties of Welded AA6082 Aluminium Alloys*, Materials Science and Engineering, Norwegian University of Science and Technology, Trondheim, 2016.
13. El-Shennawy M., Abdel-Aziz K., Omar A. A., *Metallurgical and Mechanical Properties of Heat Treatable Aluminum Alloy AA6082 Welds*, International Journal of Applied Engineering Research ISSN 0973-4562 Volume 12, Number 11, pp. 2832-2839, 2017.
14. Rudan M., *MIG zavarivanje tankih aluminijumskih limova*, 5. Seminar - Aluminij i aluminijske legure – rukovanje, priprema, zavarivanje, Pula, 2008.
15. Bajić D., *Odstranjivanje površinskog oksida pri zavarivanju aluminijuma i njegovih legura*, Zavarivanje i zavarene konstrukcije, (1/2004), Stručni rad, str. 17-20, 2003.
16. Mathers G., *The Welding alluminium and its alloys*, CRC Press Woodhead Pub, Cambridge, England 2002.
17. Levačić, D., *Zavarivanje aluminijske legure AlMg4,5Mn*, Diplomski rad, Fakultet strojarstva i brodogradnje, Zagreb, 2012.
18. Satinović A., *Utjecaj unosa toplote na čvrstoću zavarenog spoja aluminijumske legure serije 6000*, Diplomski rad, Fakultet strojarstva i brodogradnje, Zagreb, 2016.
19. Singha G., Kanga S. A., Singhb K., Singhb J., *Experimental comparison of friction stir welding process and TIG welding process for 6082-T6 Aluminium alloy*, Materials Today: Proceedings 4. pp. 3590–3600, 5th International Conference of Materials Processing and Characterization (ICMPC 2016).
20. Munchaster P.W., Practical TIG (GTA) welding, Abington publishing, Cambridge, England, 1991.
21. *https://trgovina.sigmat.hr/hr/dodatni-materijali-za-zavarivanje/24-zice-zazavarivanje -tig-postupkom-za-aluminij-i legure-bakra.html*, downloaded April 10, 2019.
22. Kos H., *Zavarljivost aluminijske legure AW6082*, Diplomski rad, Fakultet strojarstva i brodogradnje, Zagreb, 2014.
23. *https://images.homedepot-static.com/catalog/pdfImages/25/25e4a4d8-d2cc-400b-9c1c-e13fddd8d9b0.pdf*, downloaded April 10, 2019.
24. Birsan D., Scutelnicu E., Visan D., *Behaviour Simulation of Aluminium Alloy 6082-T6 during Friction Stir Welding and Tungsten Inert Gas Welding*, Recent Advances in Manufacturing Engineering, ISBN: 978-1-61804-031-2 103, pp. 103-108, 2011.
25. https://shop.messer.ba/Svi-proizvodi/1128/Argon-50-T40150.shtml, downloaded April 11, 2019.
26. Jovičić R., Cvetković R., Zrilić B., Bubalo K., *Unos toplote pri zavarivanju*, Originalni naučni rad, Zavarivanje i zavarene konstrukcije, UDK 621.791.75, str. 61- 69, 2015.
27. Stamenković D, Đurđanović M., Mitić D., *Zavarivanje postupkom „FSW“*, Stručni rad, UDK 621.791.14, Zavarivanje i zavarene konstrukcije (2/2006), str. 59-66, 2006.