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EKSPERIMENTALNA USPOREDBA MAG, TIG I FSW POSTUPKA ZAVARIVANJA ZA LEGURU ALUMINIJUMA 2024 T351

EXPERIMENTAL INVESTIGATION OF GTAW, GMAW AND FSW WELDING PROCESSES ON ALUMINIUM ALLOY 2024 T351

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Ključne reči: Zavarivanje, MAG, TIG, FSW, 2024 T351

Key words: Welding, GTAW, GMAW, FSW, 2024 T351

Sažetak: Zavarivanje je, po definiciji, spajanje dva ili više istorodna ili raznorodna materijala, taljenjem ili pritiskom, postupkom s ili bez dodavanja dodatnog materijala, s ciljem da se dobije homogen monolitni spoj koji zadovoljava standardizirane i nestandardizirane zahtjeve o nesavršenostima, mehaničkim svojstvima, deformacijama itd. Postoji ogroman broj postupaka zavarivanja pri čemu su se neki od njih veoma udomaćili u industriji i smatraju se konvencionalnim postupcima zavarivanja primenljivim na velikom broju različitih metalnih materijala. Pored njih razvijaju se i nekonvencionalne metode kojima se, pored zavarljivih materijala mogu zavarivati i materijali koji su konvencionalno teško ili potpuno nezavarljivi. Legura aluminija 2024 T351 spada u materijale koji se teško zavaruju konvencionalnim postupcima. Friction Stir Welding predstavlja nekonvencionalnu metodu zavarivanja metala u čvrstoj fazi koja je svoje najveće prednosti pokazala pri zavarivanju aluminijuma i aluminijumovih legura. Zbog toga se ovaj postupak veoma često koristi za zavarivanje legure aluminijuma iz serije 2×××. Rad se bavi eksperimentalnim istraživanjima i usporedbom MAG, TIG i FSW postupka primijenjenima na leguri 2024 T351. Istraživanja su obuhvatila ispitivanje mehaničkih i metalografskih svojstava/karakteristika zavarenog spoja.

Abstract: Welding is, by definition joining of two or more similar or dissimilar materials with application of pressure or by melting, with or without filler metal with a goal of forming monolith and homogenous joint capable to fulfill standard or nonstandard norms about imperfections, mechanical properties, deformations etc. There are numerous welding techniques and some of them are so much used in industry so they are considered as conventional for the most of different metal materials. Beside them, there are unconventional welding techniques that can be used on materials that are limitedly weldable or non weldable. Aluminium alloy 2024 T351 is a representative of by conventional techniques limitedly weldable material. Friction Stir Welding is a solid state unconventional welding technique that has shown its major advantages on welding of aluminium and aluminium alloys. That is the main reason why this technique is being used for welding of 2××× aluminium alloy series. This paper is dealing with investigation of GTAW, GMAW, and FSW applied on 2024 T351 alloy. Investigation included metallographic and mechanical testing of welded joints and comparison of results has been made..

1. INTRODUCTION

Welding is the most used joining process in the present industry. Some researches show that more than 40% of overall machining processes are bonded with welding. Welding is defined as the process of joining together two pieces of metal in a manner that bonding accompanied by appreciable inter atomic penetration takes place at their original boundary surfaces. The boundaries of welded parts more or less disappear at the weld, and integrating crystals develop across them. Welding is carried out by the use of heat or pressure or both and with or without added metal (filler material).

The palette of material capable to be joined by welding is huge – from pure metals and alloys to nonmetallic materials such polymers are. The significant number of materials is capable to be welded with materials that chemically and by properties completely differ one to another. Historically speaking welding has evolved from forging but due to great divergence of materials used in engineering, nowadays there are more than 90 recognized welding processes and only some of them just look alike to forging. The largest group of welding processes [1] involves arc welding processes and since all techniques from the group are easy to use, arc welding is considered to be conventional welding technique. Further improvements of all welding techniques aim to the improvements of processes productivity, efficiency increase, as well as application on materials that are limitedly weldable or non weldable.

However, there is still a need for joins on materials that are not weldable and have great application in technology. An example is aluminium alloy group marked 2xxx with alloy 2024 T351 as representative material widely used in automotive, aerospace, naval and railway industry. This alloy is limitedly weldable by GTAW and GMAW are processes and fully weldable by FSW process, which is still mentioned as unconventional welding process. There are some researches [2, 3, 4, 5] that show comparison of different welding processes applied on 2024 T351: GMAW and FSW, and neglect other welding processes as possible on 2024 alloy. The research done on Faculty of Mechanical Engineering Nis, Serbia was about FSW welding of 2024 alloy and heat generation processes during process [6]. Further work was expanded on application of GTAW and GMAW on 2024 T351 alloy and comparison of all processes. This paper is giving an overview on this research and gives some conclusions about weldability of 2024 T351 alloy.

2. Typical welding processes applicable for aluminium and its alloys

2.1. GTAW

Gas tungsten arc welding (GTAW), also known as tungsten inert gas (TIG) welding, is an arc welding process that uses a nonconsumable tungsten electrode to produce the weld. The weld area is protected from atmospheric contamination by a shielding gas (usually an inert gas such as argon), and a filler metal is normally used, though some welds, known as autogenous welds, do not require it. A constant-current welding power supply produces energy which is conducted across the arc through a column of highly ionized gas and metal vapors known as a plasma.

GTAW is most commonly used to weld thin sections of stainless steel and non-ferrous metals such as aluminum, magnesium, and copper alloys. The process grants the operator greater control over the weld than competing processes such as shielded metal arc welding and gas metal arc welding, allowing for stronger, higher quality welds. However, GTAW is comparatively more complex and difficult to master, and furthermore, it is significantly slower than most other welding techniques. A related process, plasma arc welding, uses a slightly different welding torch to create a more focused welding arc and as a result is often automated.

Aluminum is most often welded using alternating current, but the use of direct current is also possible, depending on the properties desired. Before welding, the work area should be cleaned and may be preheated to 175 to 200 °C. AC current can provide a self-cleaning effect, removing the thin, refractory aluminium oxide (sapphire) layer that forms on aluminium metal within minutes of exposure to air. This oxide layer must be removed for welding to occur.[25]

When alternating current is used, pure tungsten electrodes or zirconiated tungsten electrodes are preferred over thoriated electrodes, as the latter are more likely to "spit" electrode particles across the welding arc into the weld. Blunt electrode tips are preferred, and pure argon shielding gas should be employed for thin workpieces. Introducing helium allows for greater penetration in thicker workpieces, but can make arc starting difficult.[25]

Direct current of either polarity, positive or negative, can be used well. Direct current with a negatively charged electrode (DCEN) allows for high penetration. Argon is commonly used as a shielding gas for DCEN welding of aluminum. Shielding gases with high helium contents are often used for higher penetration in thicker materials. Thoriated electrodes are suitable for use in DCEN welding of aluminum. Direct current with a positively charged electrode (DCEP) is used primarily for shallow welds, especially those with a joint thickness of less than 1.6 mm. A thoriated tungsten electrode is commonly used, along with a pure argon shielding gas.

2.2 GMAW

Gas metal arc welding (GMAW), sometimes referred to by its subtypes metal inert gas (MIG) welding or metal active gas (MAG) welding, is a semi-automatic or automatic arc welding process in which a continuous and consumable wire electrode and a shielding gas are fed through a welding gun. A constant voltage, direct current power source is most commonly used with GMAW, but constant current systems, as well as alternating current, can be used.

GMAW is originally developed for welding aluminum and other non-ferrous materials in the 1940s, GMAW was soon applied to steels because it allowed for lower welding time compared to other welding processes. The cost of inert gas limited its use in steels until several years later, when the use of semi-inert gases such as carbon dioxide became common. Further developments during the 1950s and 1960s gave the process more versatility and as a result, it became a highly used industrial process. Today, GMAW is the most common industrial welding process, preferred for its versatility, speed and the relative ease of adapting the process to robotic automation. Unlike welding processes that do not employ a shielding gas, such as shielded metal arc welding, it is rarely used outdoors or in other areas of air volatility. A related process, flux cored arc welding, often does not utilize a shielding gas, instead employing a hollow electrode wire that is filled with flux on the inside.

2.3. Friction Stir Welding

Friction stir welding (FSW) is a solid-state welding process introduced during 1991-1992 by TWI London. First application of the FSW was for welding of long aluminium sheets used for railway vehicles in Japan; after that FSW was introduced by marine, aero, space, automobile and other industries around the globe. From that time, FSW is widely known as welding technique mostly used for welding of aluminium and its alloys. However, there are numerous examples of steel, bronze etc. jointed by FSW [7].

2.3.1. Principle of the FSW

At the beginning of the welding process, welding tool [8] is mounted into the rotating head of the machine, placed above the joint line on the fixed welding plates and probe tip barely touches the top of the welding plates (Figure 1, a). The main rotation axis of the welding tool is perpendicular with welding plates and the joint line. In that position welding toll starts to rotate (n revolutions per min). Probe of the welding tool (Figure 1, b) plunges into both of the welding plates (base metal) at the start point on the joint line. friction between probe and the welding plates initiates heat generation, welding plates soften in the area of friction contact between tool and plates and thread on the probe stirs the material of the welding plates. When shoulder tip touches welding plates and probe tip is very close to the backing plate, plunging of the welding tool into the welding plates stops and tool starts translation along the joint line. Moving along the joint line, weld tool's probe heats layers of material from the welding plates, cuts and stirs them and creates a vale of mixed and plasticized metal which hardens and creates monolith connection between welding pieces – weld. Shoulder tip confines upper surface of the weld while backing plate holds welding plates and confines lower surface of the weld as well. Welding process is finished when welding tool stops translation and after pulling out the tool from the joint line weld is completely finished.

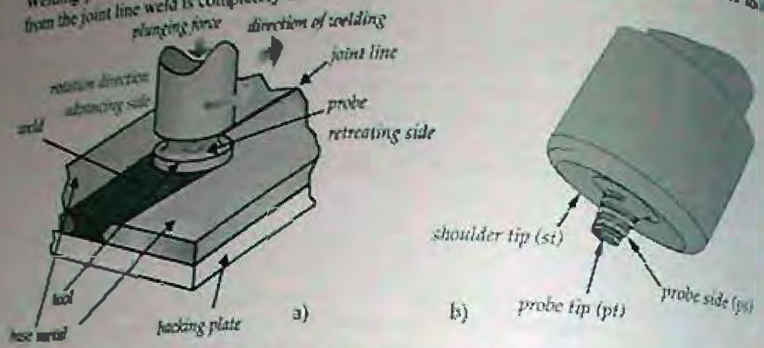


Figure 1. Friction stir welding: a) principle of the FSW, b) welding tool and its active surfaces.

In order to easily analyze the process, complete technological cycle of the FSW is explained throughout five basic phases [9, 10]: plunging, first dwelling, welding, second dwelling and pulling out. All of them are necessary for the correct weld creation.
Beside all advantages and disadvantages [9, 10, 11] compared to other conventional welding techniques, FSW has some advantages that are of importance: FSW can be used for welding of conventionally non-weldable alloys such Al series 2××× and 7××× are, temperature distortions and residual stresses of the parent material are much smaller than with other welding techniques, temperatures are significantly lower than with other welding techniques (80% of melting point temperature).

3. Aluminium alloy 2024 T351

Aluminium alloy 2024 is an aluminium alloy, with copper as the primary alloying element (Table 1, 2, 3). It is used in applications requiring high strength to weight ratio, as well as good fatigue resistance. It is poorly weldable, and has average machinability. Due to poor corrosion resistance, it is often clad with aluminium for protection, although this may reduce the fatigue strength.

Table 1. Thermomechanical properties of 2024 T351.

Module of elasticity E, N/mm^2	73100	
Density ρ_m, kg/m^3	2780	
Thermal Conductivity λ, W/(mK)	121	
Specific Heat Capacity c, J/(kgK)	875	
Electrical Resistivity ρ_{el}, (Ωmm^2)/m	0.0582	
Temperature T, °C	20-100	20-300
Coefficient of thermal expansion (average on temperature interval) α_T, 10-6/°C	23,2	24,7

Table 2. Mechanical properties of 2024 T351.

Yield strength R_e, N/mm^2	Ultimate tensile strength R_m, N/mm^2	Elongation A_5, %	Vickers Hardness HV
370	481 (exp. determined 460 to 500)	17,9	*143

* median value

Table 3. Chemical composition of 2024 T351.

Sample 1		Sample 2	
Chemical element	Mass %	Chemical element	Mass %
Sb	0.005±0.005	Sb	0.003±0.003
Sn	0.006±0.003	Sn	0.003±0.002
Pd	0.000±0.003	Pd	0.000±0.002
Ag	0.006±0.004	Ag	0.004±0.003
Ru	0.000±0.001	Ru	0.000±0.001
Mo	0.000±0.001	Mo	0.001±0.001
Nb	0.000±0.001	Nb	0.000±0.001
Zr	0.001±0.001	Zr	0.001±0.001
Bi	0.000±0.001	Bi	0.000±0.001
Pb	0.001±0.002	Pb	0.002±0.001
Se	0.000±0.001	Se	0.000±0.001
W	0.000±0.013	W	0.000±0.008
Zn	0.087±0.012	Zn	0.085±0.009
Cu	4.430±0.109	Cu	4.090±0.077
Ni	0.015±0.012	Ni	0.016±0.008
Co	0.001±0.010	Co	0.000±0.007
Fe	0.213±0.031	Fe	0.191±0.023
Mn	0.566±0.055	Mn	0.555±0.041
Cr	0.080±0.011	Cr	0.064±0.008
V	0.013±0.007	V	0.016±0.005
Ti	0.036±0.008	Ti	0.034±0.006
Al	93.164±0.489	Al	93.128±0.377
S	0.000±0.001	S	0.000±0.001
P	0.000±0.001	P	0.000±0.001
Si	0.867±0.073	Si	0.378±0.045
Mg	0.509±0.607	Mg	1.426±0.453

Due to its high strength and fatigue resistance, 2024 is widely used in aircraft structures, especially wing and fuselage structures under tension (aircraft fittings, gears and shafts, bolts, as well as clock parts, computer parts, couplings, fuse parts, hydraulic valve bodies, missile parts, munitions, nuts, pistons, rectifier parts, worm gears, fastening devices, veterinary and orthopedic equipment, structures). Additionally, since the material is susceptible to thermal shock, 2024 is used in qualification of liquid penetrant tests outside of normal temperature ranges.

4. Experimental welding on 2024 T351

By chemical composition of the 2024 alloy and its highly non-weldable properties, it is recommended for GMAW and GTAW to use filler metal based on aluminium and silicon. Experimental welding was performed on plates made of 2024 T351 with dimensions 160mm × 55mm × ≠ 6mm. Plates were plasma-cut from sheet 6000 mm × 2000 mm × ≠ 8 mm and grinded to height ≠ 6mm.

The first experimental welding was done by GTAW process. Welding was performed with Fronius TransPuls Synergic 2700 power source, filler metal was AlSi12 (EL-AlSi 12, DIN1732, manufacturer: Elektrode Jesenice). Welded plates are shown in Figure 2.

Figure 2. Welded plates: GTAW process, face of the weld.

The second experimental welding was done by GMAW process. Welding was performed with Fronius MagicWave 2600 power source, and filler metal was AlMg5 (EL-AlMn 1, DIN1732, manufacturer: Elektrode Jesenice). Welded plates are shown in Figure 3.

Figure 3. Welded plates: GMAW process, face of the weld.

The third experimental welding was performed by FSW. As welding machine a lathe was used. Lathe is not regular machine used for FSW but due to the needs of measuring (torque, forces, temperature etc.) it was necessary to adapt the lathe for the welding needs (Figure 5). This is, probably, the first recorded usage of lathe as FSW machine. Welding tool was made of steel DIN 56NiCrMoV7, annealed and tempered. Tool has cone probe (Figure 1, b) and coned shoulder tip.

Figure 4. Welded plates: FSW process, face of the weld.

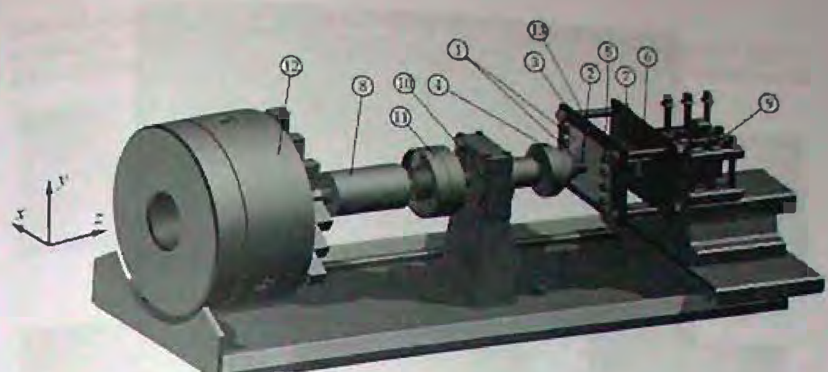


Figure 5. FSW welding place, 1-workpiece, 2 – welding tool, -3-anvil, 4-welding tool spindle, 5-bolts, 6- backing plate, 7-force sensor, 8-torque sensor, 9-tool rest, 10-housing, 11-coupler, 12-machine spindle, 13-fundamental bolts

The anvil is made of ≠16 mm height austenite steel plate X5CrNi18-10 (EN 10088-2) with purpose of low heat loss at the root of the weld. Welding was performed with 910 rpm and travel rate of 0,904 mm/s along 100 mm long joint line. Welded plates are shown in Figure 2, 3, 4.

5. Results and discussion

Visual inspection of plates welded by GTAW and GMAW has shown numerous imperfections of the welded joints – minor distortion, cracking, inclusions, gas inclusions, lack of fusion, incomplete penetration. Overall conclusion was that imperfections are coming from poor process conditions, operator error, wrong technique, and probably incorrect consumables. Visual inspection of plates welded by FSW implied minor distortion and significant toe and face flash [11].

Radiograph of welded plates joined by GMAW and GTAW only has confirmed conclusions of visual inspection (Figures 6, 7 and 8).

Figure 6. Radiograph of welded plates, GTAW.

Figure 7. Radiograph of welded plates, GMAW.

Figure 8. Radiograph of welded plates, FSW.

Radiograph of plates welded by the FSW has shown existence of 12 mm long and 0.8 mm wide longitudinal cavity [12] - on advancing side of the weld, near the midpoint of the welding span. This cavity is probably result of the axial force drop due to the poor process conditions and operator error – usage of lathe as FSW machine requires manual correction of the plunge and heel plunge depth; axial force is very important for proper weld creation during FSW and cavity is directly affected by low axial force [6]. At the moment when experimental welds were performed, there were no standards about FSW destructive testing and test samples for destructive testing (DT) were non-standard for all welded plates. The schematic of DT samples extraction is show in Figure 9.

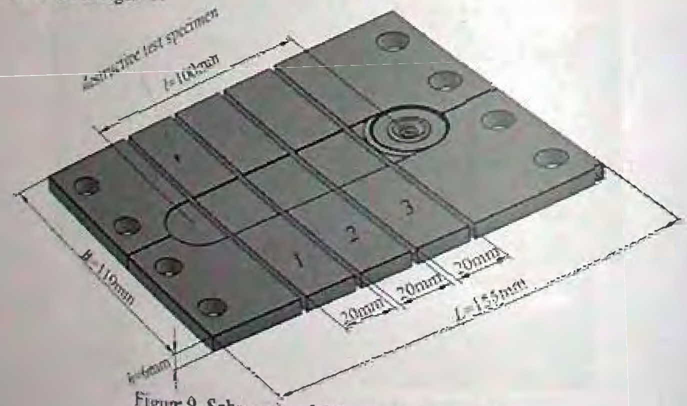


Figure 9. Schematic of DT samples extraction.

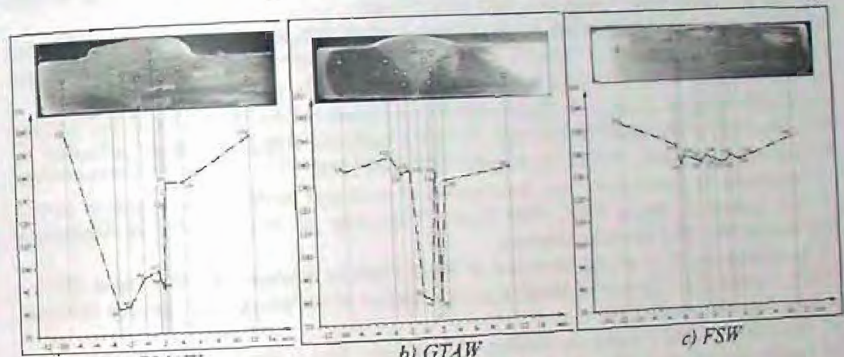
Extracted samples were used for macro- and micro- scoping investigations (Figures 10 and 11), as well as for the surface hardness investigation. Further more, specimens were used for tensile and bend testing (Table 4).

a) GMAW b) GTAW c) FSW

Figure 10. Macroscopic images of joints.

a) GMAW b) GTAW c) FSW

Figure 11. Microscopic images of joints.



a) GMAW b) GTAW c) FSW

Figure 12. Hardness of joints.

Table 4. Experimental results of tensile and bend testings.

Maximal force and ultimate tension stress	Specimen	GMAW	GTAW	FSW
F_k, kN	1	10	15	31
	2	10,5	18	45
σ_k, N/mm^2	1	76,92	115,38	238,46
	2	80,77	138,46	346,15

	GMAW	GTAW	FSW
Bending angle	20°	5°	12°
	bending angle for the parent metal was >89°		

Destruction of all specimens happened in the weld metal.

5. Conclusions

Experimental weldings of 2024 T351 alloy have showed that it represents a challenge for welding. Neither one of tested welding processes (GMAW, GTAW, FSW) has shown to be fully operational on 2024 alloy. GMAW and GTAW have shown very poorly: welds were with numerous flaws, inconsistent penetration and high porosity. Flaws indicated that welding process, welding operator and consumables might be inadequate for the proposed parent material. Assuming that all parameters were correctly selected, it is obvious that parent material is a member of the limitedly weldable materials. FSW has shown some advantages over other tested welding processes: almost flawless with minor flaws in welding operation (axial force drop), good penetration and full mixture of material. FSW has shown good properties of tension and hardness preservation along weld section. However, neither one of the welding processes has shown good bending properties.

Besides all, it is obvious that FSW has given the best results on welding of the 2024 T351 alloys, but it must be pointed out that 2024 alloy has to be treated with caution when being welded.

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SANACIJA OŠTEĆENJA OMOTAČA BIDONA NAVARIVANJEM MAG POSTUPKOM

REPARATION OF THE BIDON SHELL BY MAG SURFACING PROCESS

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Key words: high pressure vessels, reparation, corrosion, surfacing, anti corrosion protection

Abstract:

The paper discusses the causes and types of damage at the bidon shell at the plant for drying coal Kolubara Prerada Vreoci. Pressure vessels - bidons are made in 2002 of steel P 355 NH, as a replacement for the previous bidons, who had been in operation only 50% of the estimated service life, and are made of a Altherm 55. Special attention is given to the technology of GMAW (MAG) surfacing process on corrosively damaged spots, as well as on adequate application of corrosion protection on bidon shell.

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