UNIVERZITET CRNE GORE
MAŠINSKI FAKULTET
PODGORICA

MAŠINSKI FAKULTET PODGORICA

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Broj: 1548/1
Podgorica, 23.09.2020.godine

UNIVERZITET CRNE GORE
Odbor za doktorske studije

Poštovani,

U prilogu dostavljamo dopunjene Godišnje izvještaje mentora o napredovanju doktoranada, shodno Vašem dopisu, koji su razmatrani i prihvaćeni na sjednici Vijeća Mašinskog fakulteta, dana 23.09.2020. godine

S poštovanjem,

DEKAN
Prof. dr Igor Vušanović

Univerzitet Crne Gore
Mašinski fakultet

UNIVERZITET CRNE GORE
MAŠINSKI FAKULTET PODGORICA
Broj: 1548
Podgorica, 23.09.2020. godine

Na osnovu člana 64. Statuta Univerziteta Crne Gore (Bilten UCG br. 337 – posebno izdanje od 13. Februara 2015.godine), i člana 33, stav 2 Pravila doktorskih studija Univerziteta Crne Gore, Vijeće Mašinskog fakulteta u Podgorici, na sjednici održanoj 23.09.2020. godine, usvojilo je prijedlog

ODLUKE
o prihvatanju dopuna godišnjih izvještaja o napredovanju doktoranata

I Prihvata se dopuna godinjih izvještaja o napredovanju doktoranata za sledeće kandidate:

1. Vidosava Vilotijević,
2. Vuko Kovijanić,
3. Aleksandra Koprivica,
4. Radislav Brđanin.

II Prihvaćeni godišnji izvještaji mentora o napredovanju doktoranada (IM obrasci) su sastavni dio ove Odluke.

III Izvještaji se dostavljaju Odboru za doktorske studije na saglasnost.

DODSTAVLJENO:
- Odbor za doktorske studije
- St.služba
- Sekretaru
- a/a

DEKAN,
Prof. dr Igor Vušanović

UNIVERZITET CRNE GORE
Mašinski fakultet
Komisija za doktorske studije
Podgorica, 21.09.2020.

-VIJEĆU MAŠINSKOG FAKULTETA-

U skladu sa Pravilima doktorskih studija i Vodičem za doktorske studije (tačka 3.4 i 3.7) , u prilogu dostavljamo izvještaje mentora o napredovanju doktoranata navedenih u sledećoj tabeli_ Obrazac IM.

Na osnovu dostavljenog materijala i izjava mentora, u sledećoj tabeli je dat pregled zaključaka:

KANDIDAT	MENTOR	Zaključak mentora u pogledu nastavka studija
Vidosava Vilotijević IM2 obrazac	Igor Vušanović	Doktorant može nastaviti studije
Vuko Kovijanić IM1 obrazac	Uroš Karadžić	Doktorant može nastaviti studije
Aleksandra Koprivica IM2 obrazac	Nikola Šibalić Milan Vukčević	Doktorant može nastaviti studije
Radislav Brđanin IM2 obrazac	Uroš Karadžić	Doktorant može nastaviti studije

Predlažemo Vijeću Mašinskog fakulteta da usvoji izvještaje i da se isti, uz mišljenje dostave Odboru za doktorske studije UCG na dalje postupanje.

Srdačno,

Za Komisiju za doktorske studije

Prof. dr Aleksandar Vujović

DRUGI GODIŠNJI IZVJEŠTAJ MENTORA O NAPREDOVANJU DOKTORANDA

Akademska godina za koju se podnosi izvještaj	2019/20				
OPŠTI PODACI O DOKTORANTU					
Titula, ime, ime roditelja, prezime	mr Aleksandra (Mlađen) Koprivica				
Fakultet	Mašinski				
Studijski program	Mašinstvo				
Broj indeksa	4/18				
MENTOR/MENTORI					
Mentor	Doc. dr Nikola Šibalić	Mašinski fakultet Univerziteta Crne Gore, Crna Gora	Proizvodno mašinstvo		
Ko-mentor	Prof. dr Milan Vukčević	Mašinski fakultet Univerziteta Crne Gore, Crna Gora	Proizvodno mašinstvo		
EVALUACIJA DOKTORANDA*					
Koliko ste zadovoljni kvalitetom održanih susreta sa doktorandom?	☐1	☐2	☐3	☐4	☒5
(Ako je prethodni odgovor „1" ili „2" dati obrazloženje i prijedloge za poboljšanje)					
Da li je definisan plan rada sa doktorandom?	☒DA	☐NE			
Da li je doktorand ostvario napredak prema predviđenom planu rada?	☒DA	☐NE			
(Ako je prethodni odgovor „ne" dati obrazloženje i prijedloge za poboljšanje)					
Kvalitet napretka doktorandovog istraživačkog rada u periodu za koji se podnosi zvještaj je:	☐1	☐2	☐3	☐4	☒5
(Ako je prethodni odgovor „1" ili „2" dati obrazloženje i prijedloge za poboljšanje)					
Ocjena doktorandove spremnosti za konsultacije.	☐1	☐2	☐3	☐4	☒5
Ocjena planiranja i izvršavanja godišnjih istraživačkih aktivnosti i stručnog usavršavanja doktoranda.	☐1	☐2	☐3	☐4	☒5
Ocjena napretka u savladavanju metodologije naučno-istraživačkog rada.	☐1	☐2	☐3	☐4	☒5
Ocjena doktorandovog generalnog odnosa prema studijama.	☐1	☐2	☐3	☐4	☒5
Ocjenu ukupnog kvaliteta doktorandovog rada.	☐1	☐2	☐3	☐4	☒5
(Ako je prethodni odgovor „1" ili „2" dati obrazloženje i prijedloge za poboljšanje)					

*Ocjene su: 1 – nedovoljan, 2 – dovoljan, 3 – dobar, 4 – vrlo dobar, 5 – odličan

ISPUNJENOST USLOVA DOKTORANDA
Spisak radova doktoranda iz oblasti doktorskih studija koje je publikovao doktorand
1. **Aleksandra Koprivica**, Darko Bajić, Nikola Šibalić, Milan Vukčević: Analysis of Welding of Aluminium Alloy AA6082-T6 by TIG, MIG and FSW Processes from Technological and Economic Aspect, INTERNATIONAL SCIENTIFIC JOURNAL "MACHINES. TECHNOLOGIES. MATERIALS", YEAR XIV, ISSUE 5, P.P. 194-198 (2020), WEB ISSN 1314-507X; PRINT ISSN 1313-0226. 2. **Koprivica A.**, Vukčević M., Šibalić N.: Economic Analysis of Replacement of Conventional Welding Technology with Unconventional, INTERNATIONAL SCIENTIFIC JOURNAL "MACHINES. TECHNOLOGIES. MATERIALS", Issue 6/2019, P.P. 268-272 (2019), WEB ISSN 1314-507X; PRINT ISSN 1313-0226.
Obrazloženje mentora o korišćenju sprovedenih istraživanja u publikovanim radovima
Kandidatkinja mr Aleksandra Koprivica je položila sve ispite utrđene nastavnim planom i programom doktorskih studija na Mašinskom fakultetu i odbranila polazna istraživanja za izradu doktorske disertacije pred Komisijom u sastavu: prof. dr Kemal Delijić, prof. dr Sebastian Baloš, prof. dr Darko Bajić, prof. dr Milan Vukčević i doc. dr Nikola Šibalić. U sklopu polaznih istraživanja, izvršeno je zavarivanje legure aluminijuma, postupkom FSW, gdje će biti urađena komparativna analiza sa konvencionalnim postupcima zavarivanja REL i TIG. Tokom odvijanja polaznih istraživanja, utvrđene su fizikalne veličine (sila i temperatura) koje će se pratiti prilikom izvođenja procesa zavarivanja, a takođe su definisani i režimi zavarivanja i geometrija alata. Definisani su i pravci istraživanja, koji se odnose na kvalitet zavarenih spojeva i usvojene metode ispitivanja, a prikupljen je i veliki broj literaturnih izvora. Komisija je predložila da naslov doktorske teze glasi: „Komparativna analiza i optimizacija procesa zavarivanja aluminijumske legure serije 1xxx". Izvještaj Komisije za ocjenu polaznih istraživanja je usvojen na sjednici Senata Univerziteta Crne Gore 24.12.2019. godine. Posle odbrane polaznih istraživanja, kandidatkinja mr Aleksandra Koprivica je aktivno učestvovala u sprovođenju usvojenog gantograma planiranih aktivnosti. Nastavila je dalja istraživanja u smislu, projektovanja alata i pomoćnih pribora koji će se koristiti pri izvođenju glavnog eksperimenta, kao i svih ostalih sistema koji će se koristiti u ovom istraživanju. Takođe, posvetila je veliku pažnju i izradi samih alata i pribora, od kojih su izrađeni: set od devet alata za zavarivanje različitih geometrijskih dimenzija i oblika, u skladu sa usvojenim eksperimentalnim planom, glavna noseća ploča sa držačima za stezanja materijala koja je prilagođena EN standardima za zavarivanje uzoraka od aluminijuma, oslona ploča od kaljenog i fino brušenog čelika koja definiše korjenu stranu zavara, set od četiri nosača glavne oslone ploče na kojoj će se montirati senzori za mjerenje sila, kao i zglobni umetci koji dozvoljavaju pomjeranja u tri normalna pravca (aksijalnom, longitudinalnom i bočnom). Kandidatkinja je pored ovih aktivnosti na izradi svoje doktorske teze učestvovala i u pisanju naučnih radova iz oblasti doktorske disertacije koje je publikovala u međunarodnom časopisu INTERNATIONAL SCIENTIFIC JOURNAL "MACHINES. TECHNOLOGIES. MATERIALS". Pošto kandidatkinja Koprivica živi i radi u Trebinju B&H, a zbog novonastale situacije i pojave pandemije nije bila u mogućnosti da dolazi na istraživačko mjesto, te realizacija postavljanja izrađene opreme, pomoćnih probora i izvođenje eksperimentalnih istraživanja nijesu išli predviđenom dinamikom. Takođe, zbog ove situacije kandidatkinja nije bila u mogućnosti da putuje van zemlje i posjećuje naučno istraživačke skupove, na kojima bi prezentirala svoje rezultate.

Ocjena o aktivnostima sprovedenim na pisanju i objavljivanju naučnih radova.	☐1 ☐2 ☐3 ☐4 ☒5

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Obrazac IM: Godišnji izvještaj mentora o napredovanju doktoranda

SAGLASNOSTZA NASTAVAK STUDIJA	
Može li doktorand nastaviti studije?	☒ Da ☐ Da, uz određene uslove ☐ Ne
(Ako je prethodno dat odgovor pod „Da, uz odredjene uslove" ili „Ne" dati obrazloženje i prijedloge za poboljšanje)	
Napomene	
(Popuniti po potrebi)	
IZJAVA MENTORA I KOMENTORA	
Bez obzira na ograničenja uslovljena pandemijom i pretežno eksperimentalnom prirodom doktorske disertacije, koleginica Koprivica je pokazala punu posvećenost i ozbiljan pristup istraživačkom radu, te smo mišljenja da će kandidatkinja uspješno nastaviti rad na svojoj doktorskoj disertaciji.	
U Podgorici, 11.09.2020. godine MP	Doc. dr Nikola Šibalić Nikola Šibalić Prof. dr Milan Vukčević

Prilog dokumenta sadrži:

Kopije objavljenih radova iz oblasti doktorske disertacije.

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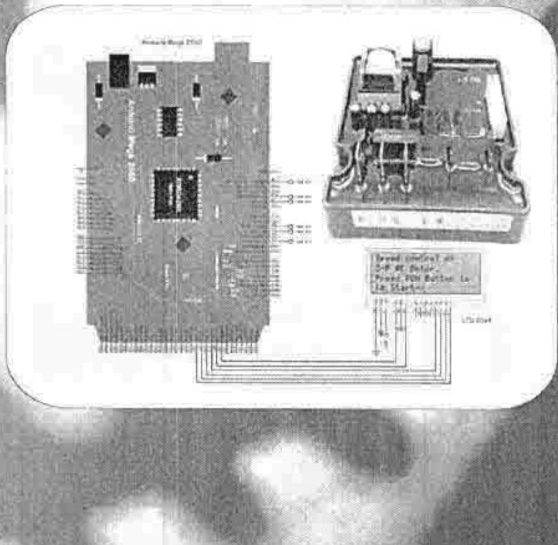

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Analysis of welding of aluminium alloy AA6082-T6 by TIG, MIG and FSW processes from technological and economic aspect

Aleksandra Koprivica, Darko Bajić, Nikola Šibalić, Milan Vukčević
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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].

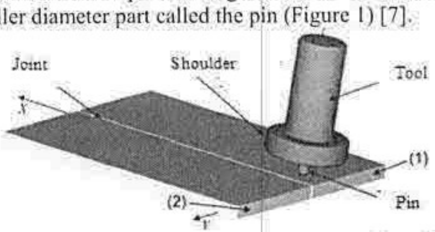

Figure 1. Tool and work pieces before welding [8]

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 °C and aluminum of about 660 °C, 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 °C, 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.

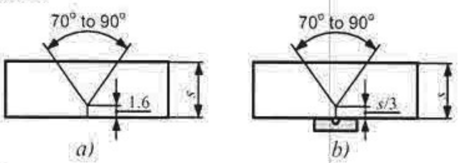

Figure 2. *Preparation of weld seams: a) with TIG procedure for material of thickness 6 mm; b) in the MIG process for a material thickness of ≈ 6 mm [16]*

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.

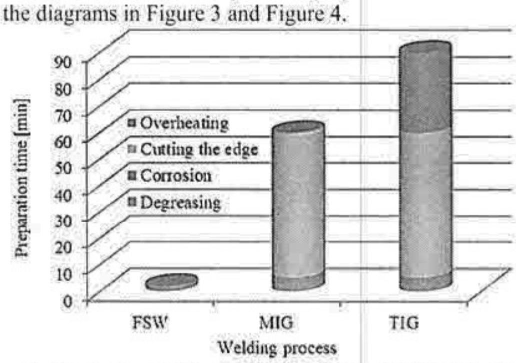

Figure 3. *Preparation time of material AA6082-T6 of thickness 6 mm for FSW, MIG and TIG welding*

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].

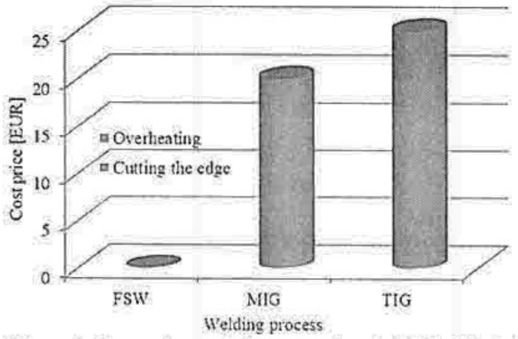

Figure 4. *Costs of material preparation AA6082-T6 of thickness 6 mm for FSW, MIG and TIG welding*

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.

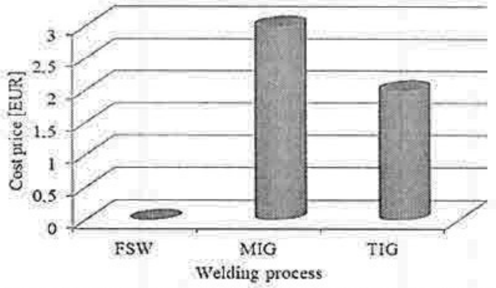

Figure 5. *Costs of additional material required for welding AA6082-T6 of thickness 6 mm FSW, MIG and TIG*

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.

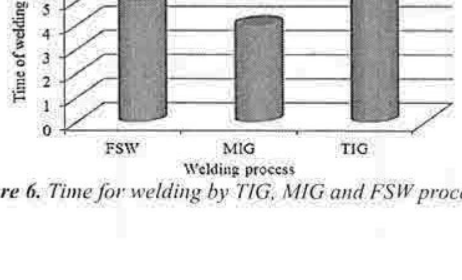

Figure 6. *Time for welding by TIG, MIG and FSW processes*

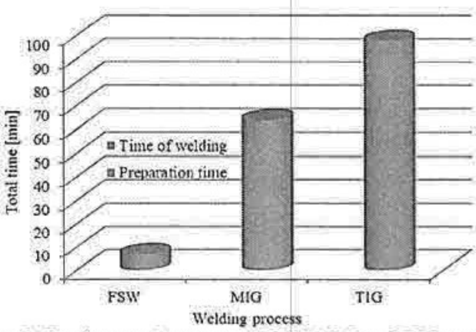

Figure 7. *Total time of extraction FSW, MIG and TIG processes*

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.

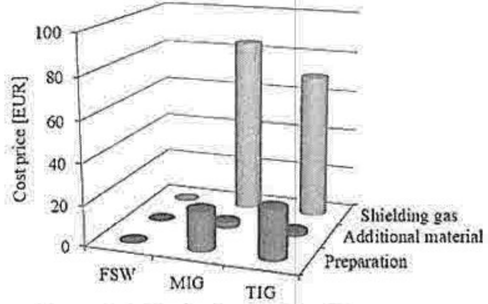

Figure 8. *Individual costs of welding processes*

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]:

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

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.

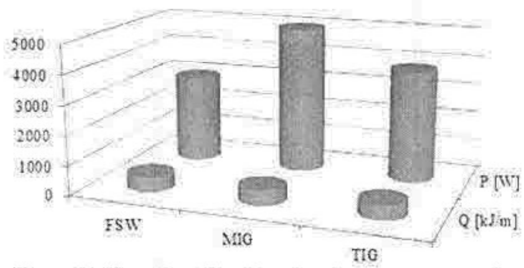

Figure 9. *Quantity of heat input and power consumption*

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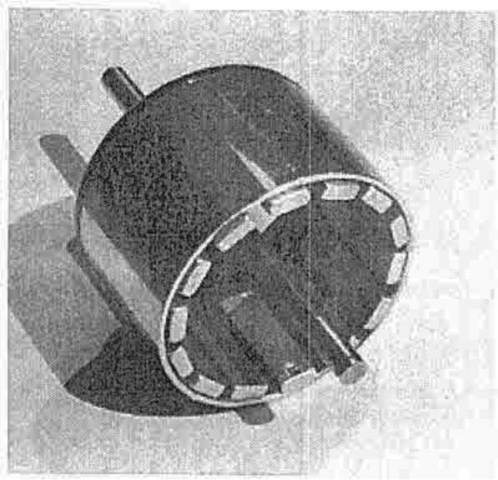

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ECONOMIC ANALYSIS OF REPLACEMENT OF CONVENTIONAL WELDING TECHNOLOGY WITH UNCONVENTIONAL

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Apstract: *The technological and social environment in which we live changes very quickly. Competition grows from time to time, so it is a constant tendency towards product and service providers to achieve a competitive advantage, and thus satisfy the needs of consumers. In order to achieve the above, the organization is often at a crossroads where important decisions are needed, which are most often related to the investment in new equipment or technology. Also, in parallel with the decision to invest in new equipment or technology, a decision is made to retain or upgrade the existing one. In order to make the right decision, often well-known postulates of engineering economies are often used, which include systematic assessment of the economic values of the proposed solutions. In order for economies to be acceptable, solutions must show the existence of a positive relationship between long-term benefits and long-term costs, as well as ensuring the success and survival of companies in the market. In this paper, the economic cost-effectiveness of replacing the existing electrolytic welding technology with insoluble electrode in inert gas (TIG), the new FSW welding technology is considered.*
KEY WORDS: TIG, FSW, ECONOMIC ANALYSIS, REPLACEMENT, BENEFITS, COSTS.

1. *Introduction*

An important decision facing a large number of organizations, both productive and service providers, is whether existing assets or technologies need to be withdrawn from use, replaced by new ones, or simply retained. Living in a time of strong market competition, which grows at an enormous speed from time to time, high productivity criteria are set before product manufacturers and service providers, which primarily relate to the higher quality of goods and services, and shorter delivery times. In this regard, in order to satisfy the above criteria, the most common is the implementation of the decision, which refers to the replacement of existing assets or technologies, new ones.

The replacement problem, in order to improve operational efficiency and strengthen the competitive position in the global market, requires a thorough analysis and consideration of all the accompanying problems.

The engineering economy provides assistance in deciding on the replacement of assets or technologies, based on an analysis of several proposed solutions. Often, for the use of resources, during the substitution analysis, the term "defender" is used, while the proposed alternatives, which refer to new ones, are called "challengers".

However, the adoption of a specific substitution decision can be influenced in many ways. Thus, for sometime, it may be acceptable for the existing product or technology to be completely withdrawn from use, without replacement, while for some time a decision is made to retain it, but only for spare use. Also, the decision to substitute is influenced by the fact that the increase in market demands can be met by expanding existing capacities or by increasing the capacity of available funds.

This paper analyzes the replacement of conventional welding technology with an unconventional one. Of the conventional technologies, one of the methods of arc welding (TIG) was taken into account, while the friction stir welding procedure - FSW was taken as an unconventional process.

When considering, attention is focused on several important factors, which have the greatest impact. Also, consideration was given to the economic parameters of the analyzed technologies.

2. *Replacement analyses*

2.1. Reasons for replacement

There are numerous reasons that make the questionable profitability of using existing assets or technology, and are most often followed by negative financial indicators. All influential factors, leading to the above mentioned adverse effects, can be grouped into three groups [1]:

- **Physical damage to resources.** Changes related to physical characteristics. Continued use of resources ("aging") leads to a reduction in its efficient functioning. All this leads to a number of related problems such as: increasing planned and unplanned overhauls, increasing maintenance costs, increasing energy consumption, increasing the time needed to perform the operation, etc. Also, during the use of funds, an unexpected event can occur (an accident), which affects the physical state of the assets, and thus impair the economy and the possibility of further use;
- **Changed requirements**. Capital assets are used to produce goods in order to meet the needs of consumers, using existing technology. Changes in demand or a change in product design may be reflected in a change in cost-effectiveness;
- **Technology**. The impact of technology change varies depending on the type of asset itself. Changes in technology, in general, positively affect: costs per unit of production, quality of products or services, etc., and therefore often make decisions about replacement of existing funds, new funds.

Factors that relate to physical damage to assets and changed market requirements may refer to different categories of limitation. In the case of a replacement problem, they do not need to be included in only one of the above factors, but can simultaneously be influenced by factors from all three groups. However, notwithstanding everything, replacing old funds with new assets is most often a good economic opportunity for an organization.

2.2. Factors to be considered in the replacement analysis

There are several factors that must be considered in the replacement analysis. Once these factors and their dependence are identified, the likelihood of experiencing difficulty in analyzing substitution is low. The most important factors are [1]:

- recognizing and accepting mistakes from the past,
- lost costs,
- existing value and neutral viewpoint,
- economic life of "challangrs",
- the remaining economic life of "defenders" and
- consideration of income tax.

Recognizing mistakes from the past. The economic focus of the analysis study is always focused on the future. Any estimation errors made in the previous study, which are associated with existing assets, are not significant. In most resemblances, the inability to predict the future situation is anticipated during the initial assessment period. The organization is often at a crossroads, where it is necessary to decide whether, on the one hand, one should live with all the mistakes and differences from the past, or, on the other hand, to exist in a healthy competitive position in the direction of the future. The most common fears that arise when making this decision is the possibility of losing the value of the existing asset due to the replacement. However, regardless of whether there will be a replacement of the asset or not, the facts show that the loss is inevitable in any case.

Lost Costs. It is very important to define a non-returnable loss at a particular point, which is the difference between the carrying amount of the asset and its current market value. Non-refundable costs are not a relevant factor in the analysis of substitution unless they have an impact on income tax, because in this case they must be taken into account in an economic study. It is clear that in practice, when analyzing the replacement, a major error can be made if the non-refundable costs are incorrectly calculated.

Existing values and neutral viewpoint. The introduction of a neutral viewpoint aims to bring the concept of value to the existing asset of the "defender" closer. In fact, a neutral viewpoint is an attitude that would occupy a third (impartial, objective) person in determining the current market value of the asset used. This viewpoint forces analysts to focus on current and future cash flows during the exchange analysis, thus avoiding the temptation to retain on past (non-refundable) costs. The current market value of the asset is the exact amount of capital investment that will be allocated to the existing asset in the replacement process. Any new investment cost required to upgrade the existing asset in order to achieve competitiveness with the "challenger" should be added to the current market value of the asset in order to be relevant in the replacement analysis. At a neutral point of view, it takes into account that the assets of the "defender" are equal to the sum of the cost, which is equal to the current market value of the unsold asset and the cost of superstructures, with the aim of achieving co-curricularity with the best available "challenger".

The economic life of the "challenger". The economic life of the asset is often shorter than useful or physical life. During the analysis it is necessary to know the economic life of the "challenger" for the reason that a comparative analysis between the existing and the new asset is precisely based on their economic life. Economic data on the "challenger" are periodically updated, and then the replacement analysis is repeated, in order to ensure a continuous assessment of the possibilities for improvement.

The economic life of the "defender". It must be taken into account when comparing the current defender with the "challenger", as it is a comparison of different ages. The lifetime of a "defender" should be longer than its economic life, until its marginal cost is less than the minimum equivalent of the "challenger" annual cost in his economic life.

The importance of the consequences of income tax. Substituting an asset often results in a gain or loss on the sale of depreciable assets. Consequently, in order to carry out a precise economic analysis in such cases, studies must be made after the taxation process. It is evident that the occurrence of taxable profit or loss during replacement can have a significant impact on the result of engineering studies.

3. *Project profitability assessment*

Because patterns of capital investment, revenue (or saving) cash flows, and disbursement cash flows can be quite different in various projects, there is no single method for performing engineering economic analyses that is ideal for all cases. Consequently, three methods are commonly used: Present Worth (*PW*), Annual Worth (*AW*), Future Worth (*FW*). This methods convert cash flows resulting from a proposed solution into their equivalent worth at some point in time by using an interest rate known as the Minimum Attractive Rate of Return (*MARR*) [2].

The Present Worth Method. To find the *PW* as a function of *i%* (per interest period) of a series of cash inflows and outflows, it ic necessary to discount future amounts to the present by using the interest rate over the appropriate study period (years, for example) in the following manner:

(3.1) $$PW\ (i\%) = \sum_{k=0}^{N} F_k (1+i)^{-k}$$

where are: i - effective interest rate or MARR, per compounding period, k - index for each compounding period ($0 \le k \le N$), Fk - future cash flow at the end of period k and

N - number of compounding periods in the planning horizon (i.e., study period).

The relationship given in Equation 3.1 is based on the assumption of a constant interest rate throughout the life of a particular project. If the interest rate is assumed to change, the PW must be computed in two or more steps.

The Future Worth Method. The future worth metod is based on the equivalent worth of all cash inflows and outflows at the end of the planning horizon (study period) at an interest rate that is generally the *MARR*.

Also, the *FW* of a project is equivalent to its *PW*; that is, $FW = PW(F/P,\ i\%,\ N)$, If $FW \ge 0$ for project, it would be economically justified. Equation 3.2 summarizes the general calculations necessary to determine a project's future worth [2]:

(3.2) $$FW\ (i\%) = \sum_{k=0}^{N} F_k (1+i)^{N-k}.$$

The Annual Worth Method. The Annual Worth (*AW*) of a project is an equal annual series of money amounts, for a stated study period, that is equivalent to the cash inflows and outflows at an interest rate that is generaly the *MARR*. Hence, the *AW* of a project is annual eqivalent revenues or savings (*R*) minus annual equivalent expenses (*E*), less its annual equivalent Capital Recovery (*CR*) amount. An annual equivalent value of *R*, *E*, and *CR* is computed for the study period, *N*, which is usually in years. In equation form the *AW*, which is a function of *i%*, is [2]:

(3.3) $$AW\,(i\%) = R - E - CR(i\%).$$

Also, we need to notice that the *AW* of a project is equivalent to its *PW* and *FW*. That is, *AW* = *PW(A/P, i%, N)*, and *AW* = *FW(A/F, i%, N)*. Hence, it can be easily computed for a project from these equivalent values. As long as the *AW* is greater than or equal to zero, the project is economically attractive. An *AW* of zero means that an annual return exactly equal to the *MARR* [2].

4. *Economic aspects of TIG and FSW methods of welding*

In modern industrial production, every production process should be tested in terms of economy. For every company that invests in a new process or technology, it is important to carefully consider all the economic aspects that accompany this process, or technology.

In this paper, the emphasis is placed on welding 6 mm thick sheets, made of Al alloys in the 6000 series (AA 6082-T6). A comparison in terms of cost-effectiveness has been made with regard to welding by electrolytic method of insoluble electrode in protection of inert gas (TIG), on the one hand, and on the other hand, friction stir welding (FSW).

Friction stir welding (FSW) was developed and patented by TWI, Cambridge, UK, in 1991, whose main goal was to overcome the problems that occurred during welding (primarily aluminum alloys) by the process melting. Since its introduction, this process has been constantly improved and the scope of its application has been expanded. FSW is a solid state coupling process using a combination of heat and mechanical work to produce high-quality compounds, without the usual defects characteristic of the melting process [3].

The process itself has found industrial applications in shipbuilding, the aviation industry, auto-moto industry, etc. Additional material or protective gas is not used. The process can be easily automated, so there is no need for highly qualified workforce. The working environment in the case of FSW is cleaner than in arc welding, and there are also no harmful gases, smoke, UV and other harmful radiation. No special preparation of surfaces or edges of slabs prior to welding is required, which greatly reduces costs [4].

What makes the FSW process more economical compared to TIG welding are primarily the costs that are included in the TIG procedure, while in FSW welding they are not present. The estimation of cost-effectiveness is carried out on an annual basis, with the assumption that the welding is performed in one shift, during the working week (ie, it is assumed that the effective working time is about 6 hours during one shift).

Welding of Al plate, thickness of 6 mm, in TIG welding, requires the preparation of these plates, which relates to the edging of the edges by the milling process. In addition, the welding of Al alloys is difficult due to the presence of a layer of Al oxide on the surface of the panels, so for the high-quality TIG welding it is necessary to remove the oxides by means of chemical reagents and mechanically. In addition to all of the above, it is recommended that during TIG welding of materials, whose thickness is greater than 3 mm, it is preheated for 30 minutes, which again requires certain costs. As FSW welding is known to be solid, it should be noted in this connection that the costs of preparing the material are minimized, i.e. there are no [5].

In addition to the cost of preparing welding materials, the TIG welding process also shows the cost of additional material, while FSW is a welding process without additional material. When welding the AA6082-T6 alloy with a thickness of 6 mm, an additional material made of an alloy of ER4043 [5] is used.

In addition to the above, large costs are present in the use of a protective atmosphere. In order for the TIG procedure to be performed well, it is necessary to use a protective atmosphere. It is these costs, to a large extent, that contribute to the fact that the TIG procedure falls into high-cost procedures.

According to [5], the total cost of TIG welding for the 1m alloy AA6082-T6 is 80 €, and the total time required for preparing the material and welding 1 m of said alloy is 90 minutes.

According to the literature source [6], the welding power of AA6082-T6 for the TIG process is 3850 W, while for the FSW process it is 3382 W. Therefore, the difference in the cost of electricity consumption is negligible, so when considering the economy, it will not be taken consider.

However, for the execution of FSW welding, a special tool designed for this type of welding is required. Tool construction is a crucial parameter that influences the quality of the welded joint. On the tool itself, welding forces act, which lead to negative effects, such as tool wear. In addition to the active forces, in the process of welding, the tool generates heat through the tool, which implies that the tool must be made of adequate material, which is adapted to the base material. According to the recommendation of the literature source [7], for the FSW welding of the AA6082-T6 alloy, a tool made of steel for working in hot state JUS C.4751 is used [8]. In addition, the tool has to be thermally processed so that its hardness meets certain requirements, and thus processed smoothly executes the welding process. The tool is made by cutting, and therefore the estimated costs of material and tool making, and its thermal processing are 100 €/piece. As stated above, during the welding process itself, due to the high resistance of the welding material and the forces that act during the process, the tool suffers from some damage, thus losing its high-quality functionality, so it is necessary to replace it with new ones.

5. *Example of analysis of technology replacement*

The company that deals with welding aluminum panels is considering investing in new welding technology (FSW), which would replace the existing electrolytic welding technology with insoluble electrode in inert gas (TIG).

If an effective working time of 6h is assumed during one shift (five working days a week and 52 weeks during the year), the use of TIG technology leads to costs (preparation of materials, additional material and protective gas) in the amount of 20000 € / year [5, 6]. TIG welding equipment could be sold on the free market for 1300 € and written off after five years of exploitation. The investment in a new, modern equipment costs 70000 € [9]. The market value after 5 years of use is 50000 € [2], with the annual spending on the special tools necessary for the implementation of welding to be 2400 €. If the minimum acceptable wage rate (*MARR*) for the company is 20% per year, it should be opted for economically more cost-effective technology.

Solution: The first step in solving this problem is the determination of the investment value of the "defender" (equipment for TIG welding). From a neutral point of view, the investment value of a "defender" represents its current market value and is 1300 €. It will be approached to calculate the *PW*, and based on this, decide to retain or replace existing technology with a new one:

Defender:

$$PW\ (20\%) = -1300\ € - 20000\ €(P/A, 20\%, 5) - 61100\ €$$

Challenger:

$$PW\ (20\%) = -70000\ € - 2400\ €(P/A, 20\%, 5) + 50000\ €(P/F, 20\%, 5) = -57082,12\ €.$$

According to the calculated, the *PW* "challenger" is greater than the PW "defender". In this way, it was pointed out that TIG welding technology was necessary to replace FSW technology. The diagram in Figure 1 shows the difference between the present value of the equipment and the future value of the equipment. It is evident that during the five-year period under review, the economic advantage of FSW technology is significant in relation to TIG welding technology.

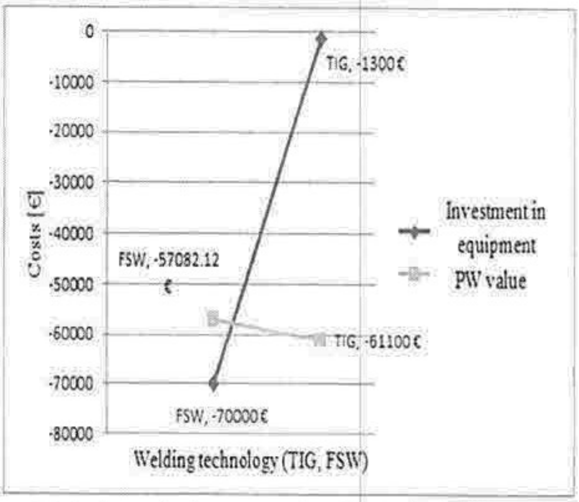

Fig 1. *A graph of present values "defender" (TIG) and "chalanges" (FSW)*

Figure 2 graphically depicts the cash flows of the "defender", which refers to the TIG welding process and the "challenger", which refers to investment in new technology (FSW). In this case, the "challanger" is a better alternative than the "defender" because it has a higher PW value. Therefore, the extra benefits of investing in the new technology of 70000 € ("challanger") have a present value that is: -57082,12 € - (-61100 €) = 4017,88 €, or:

$$PW\ (20\%)_{Difference} = -68700 + 17600\ (P/A,\ 20\%,\ 5) + 50000\ (P/F,\ 20\%,\ 5) = 4017,88\ €.$$

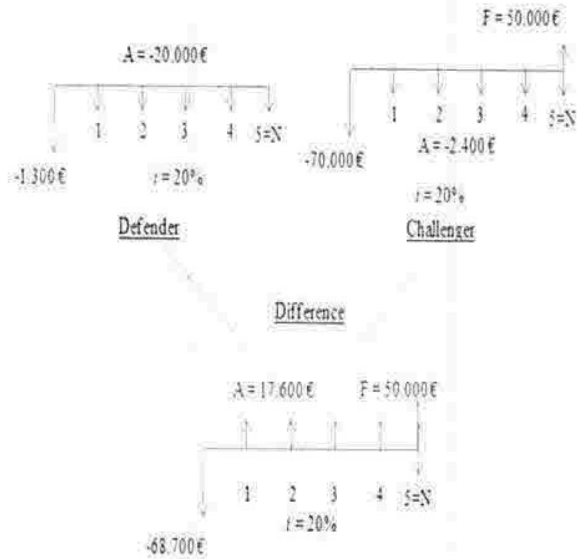

Fig 2. *Cash flow diagram of the defender, challenger and their differences*

6. Conclusions

In the pursuit of market survival and the provision of profits, in times of strong market competition and increasingly demanding consumer needs, the organization often makes decisions about replacing existing or new technologies, which will, in a longer period of time, ensure its survival and growth in a competitive market.

Analyzing and comparing the costs of existing and new technology (resources) are basic aspects of engineering practices. The consideration of the economic cost-effectiveness of replacing the existing arc welding technology with insoluble electrode in inert gas - TIG ("defender"), new welding technology with mixing - FSW ("challanger") was carried out on the basis of the known postulates of the engineering economy, using the current value method (PW). Based on this method, in the considered five-year period, it was concluded that the investment in new technology is much more favorable than the alternative to retain the existing welding technology, which in the considered period leads to a large number of costs, which primarily relate to costs: preparation materials, costs of additional materials and protective gas costs.

All of the above points to the fact that making a decision to invest in new welding technology for the company under consideration is the correct path to maintaining and strengthening market competitiveness and ensuring the profit and survival of the organization on the market.

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