

# INFLUENCE OF FRICTION STIR WELDING ( FSW) ON MECHANICAL AND CORROSION PROPERTIES OF AW-7020M AND AW-7020 ALLOYS

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## ABSTRACT

*Friction welding associated with mixing the weld material (FSW - Friction Stir Welding) is an alternative to MIG and TIG welding techniques for Al-alloys. This paper presents experimental results obtained from static tension tests on specimens made of AW-7020M and AW-7020 alloys and their joints welded by using FSW method carried out on flat specimens, according to Polish standards: PN-EN ISO 4136:2011 and PN-EN ISO 6892-1:2010. Results of corrosion resistance tests are also presented. The tests were performed by using the electrochemical impedance spectroscopy (EIS). EIS measurement was conducted with the use of three-electrode system in a substitute sea water environment (3,5% NaCl - water solution). The impedance tests were carried out under corrosion potential. Voltage signal amplitude was equal to 10mV, and its frequency range - 100 kHz ÷ 0,1 Hz. Atlas 0531 EU&IA potentiostat was used for the tests. For the tested object an equivalent model was selected in the form of a substitute electric circuit. Results of the impedance spectroscopy tests are presented in the form of parameters which characterize corrosion process, as well as on Nyquist's graphs together with the best-fit theoretical curve.*

*Analysis of the test results showed that the value of charge transfer resistance through double layer,  $R_{ct}$ , for the FSW-welded specimen, was lower than that for the basic material, and that much greater difference was found in the case of AW-7020M alloy.*

*The impedance spectroscopy tests showed that both the FSW-welded joints and basic material of AW-7020M and AW-7020 alloys were characterized by a good resistance against electrochemical corrosion in sea water environment, and that FSW-welded joints revealed a greater corrosion rate.*

*The performed tests and subject-matter literature research indicate that application of FSW method to joining Al-alloys in shipbuilding is rational.*

**Keywords:** Al-alloys, mechanical properties, electrochemical impedance spectroscopy (EIS), corrosion, FSW, friction welding

## INTRODUCTION

Such properties of Al-alloys as: non-magnetism, high value of the relative strength factor  $R_{p0,2}/\rho$ , relatively good corrosion resistance in sea water and atmosphere, weldability as well as good fracture toughness (also in low temperatures) have decided on wide range of their application in world shipbuilding [2].

In shipbuilding industry are widely used Al-alloys of 5xxx series whose higher strength properties of parent material are reached as a result of cold working. However influence of temperature during welding such alloys results in strength degradation in heat affected zone (HAZ) down to their properties in mild state, i.e. by abt. 20 ÷ 30%, which is hard to be estimated precisely. Qualitative changes in load-carrying ability analysis are especially visible for welded aluminium structures, in HAZ [11]. The phenomena are specific for majority of 5xxx series Al-alloys. Al-alloys in the annealing

state „O”, raw state „F” as well as the annealing and light-hardening state „H111” do not suffer the above mentioned destruction [8].

In the 1990s high interest started to be paid to the weldable Al-alloys of 7xxx series (Al-Zn-Mg), characteristic of much higher strength properties compared to those of 5xxx series Al-alloys. A disadvantage of Al-Zn-Mg alloys is their dependence to stress corrosion fractures in sea-water environment, especially when total (Zn+Mg) amount exceeds 6% [2]. Due to application of an appropriate heat treatment consisting in solutioning and artificial ageing, resistance of the alloys to environmental destruction reached a satisfactory level. In contrast to Al-Mg alloys, strength properties of welded joints of Al-Zn-Mg alloys reach similar values as those of parent material [1]. Unfortunately, their resistance to corrosion, especially stress corrosion in sea water, drastically drops. One of the most common, high-strength Al-alloys of 7xxx series applied in shipbuilding is 7020 Al-alloy. The above

mentioned dependence to stress corrosion fracture in sea-water environment which occurs first of all in welded joints results in undertaking research towards modification of the alloy. As a result, was developed the alloy marked 7020M whose chemical composition was changed (amount of Zn+Mg was increased to >6,55 % at increasing the amount of Cr and Zr) [8].

The joining of aluminium and their alloys by welding is rather difficult due to its specific properties. Principal difficulties which occur during welding Al-alloys result from: a high affinity between aluminium and oxygen and forming a hard-melting oxide,  $Al_2O_3$  (in 2060 °C), high heat conductivity, high thermal expansion of Al-alloys, high casting shrinkage (resulting in post-welding stresses and deformations), rather large strength drops in welding temperatures, losing some alloying components such as Mn Zn or Li in welding temperatures [8]. The shortly described principal difficulties associated with welding Al-alloys encourage to search for other methods of joining such materials. The friction stir welding (FSW) can serve as an alternative in case of butt joining the plates [7, 10, 12].

The technology of friction welding associated with mixing the weld material (Friction Stir Welding) was developed and patented in 1991 by Welding Institute (TWI), Cambridge, UK. In the method for heating and plasticizing the material, was used a tool with rotary arbour, located in the place of joining the plates pressed tight together. After making the tool arbour rotating, friction heating and plasticizing the material of plates in its direct neighbourhood, slow move of the whole system along contact line, is initiated. FSW is a method of friction welding of such materials in solid state so far as Al-alloys, copper and stainless steels. The main advantage of the method is easiness of producing joints of high, repeatable properties [3,4,5]. Because the friction welding technology is applicable to materials in solid state (below their melting temperatures), strength properties of joints produced this way may be higher than those reached by using the arc welding techniques (MIG, TIG) [13]. This is especially important when to take into account that plates made of Al-alloys are often subjected to heat treatment. Therefore the traditional welding methods, by charging large heat amount, introduce important changes in structure of joined material (especially in its heat affected zone). It causes substantial decrease of strength properties of welded joints, but first of all, a drastic drop in their corrosion resistance (stress and fatigue corrosion), especially in such aggressive environment as sea water.

This work is aimed at determination of influence of friction welding with the use of Friction Stir Welding (FSW) method, on corrosion resistance of AW-7020 and AW-7020M alloys in sea water. Static tension tests were also conducted to determine mechanical properties of joints of the selected alloys welded by using FSW method.

## TEST METHOD

For the tests EN AW-7020M and EN AW-7020 alloys were selected. The alloys were subjected to T651- heat treatment. Their chemical composition is shown in Tab. 1.

Tab. 1. Chemical composition of 7020M and 7020 alloys [9]

No. of melt	Chemical composition [%] of 7020M alloy										
	Zn	Mg	Cr	Zr	Ti	Fe	Si	Cu	Mn	Ni	Al
507	5.13	1.9	0.16	0.15	0.071	0.27	0.15	0.08	0.057	0.006	rest
635	4.81	1.9	0.17	0.12	0.016	0.31	0.21	0.09	0.06	0.006	rest
Type of heat treatment: T651;super saturation - heating up to 480°C for 50 min, cooling with hot water of min. 70°C, natural ageing for 0-4 days at 20°C, two-stage artificial ageing 95°C/8h+150°C/8h.											
No. of melt	Chemical composition [%] of 7020 alloy										
	Mg	Mn	Ti	Zn	Cr	Si	Fe	Cu	Zr	Al	
1.25	0.18	0.034	5.3	0.14	0.16	0.32	0.05	0.04		rest	
Type of heat treatment: T651;super saturation – heating up to 430°C for 45 min, cooling with water of min. 15°C, natural ageing for 0-6 days at 20°C, artificial ageing - 120°C/96h.											

Butt joints of plates of the thickness  $g = 10$  mm were made by using FSW method. The plates of both the tested alloys were welded on both sides at the same welding parameters.

Schematic diagram of the friction stir welding connected with mixing the weld material (FSW) is presented in Fig. 1, and its parameters – in Tab. 2.

Tab. 2. Parameters of FSW welding procedure for 7020M and 7020 alloys

Dimensions of arbour			Tool slope angle $\alpha_z$ [°]	Tool rotational speed $V_n$ [rpm]	Welding linear speed $V_z$ [mm/min]
D [mm]	d [mm]	h [mm]			
24	5,5	7,8	88,5	710	240

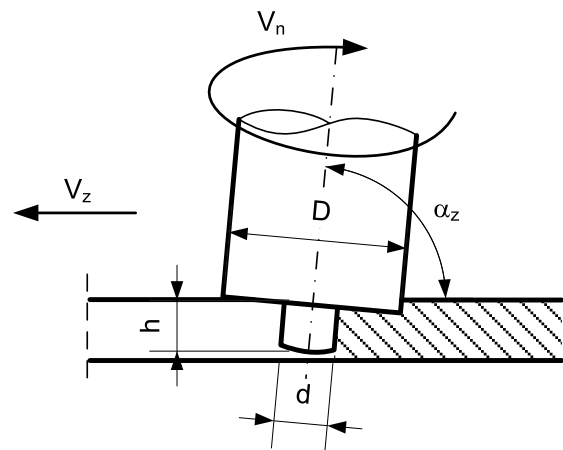


Fig. 1. Schematic diagram of FSW welding procedure[5]

## STATIC TENSION TEST

Static tension tests were performed to determine mechanical properties of plates made of 7020 and 7020M alloys and their joints produced by using FSW method. Flat specimens cut perpendicularly to milling direction were used. The tests were conducted in ambient temperature of  $+ 20\text{ }^{\circ}\text{C} \pm 2$ . The tension tests were carried out in accordance with Polish standards: PN-EN ISO 4136:2011 and PN-EN ISO 6892-1:2010 with the use of EU-40 testing machine of force range up to 200 kN.

## TESTS OF ELECTROCHEMICAL CORROSION RESISTANCE

Measurement of electrochemical corrosion resistance was performed by using the electrochemical impedance spectroscopy method (EIS) in accordance with ASTM G 3 and ASTM G 106 standards [15, 16].

The applied three-electrode system was consisted of the following elements: specimen, an auxiliary (polarizing) electrode of platinized titanium and a reference electrode (saturated calomel electrode). The electrodes were placed into a vessel filled with 3,5 % NaCl –water solution. The active surface of the specimens was equal to  $1\text{ cm}^2$ .

During measurement the electrolyte was all the time stirred by means of a magnetic mixer. The specimens were degreased in advance.

Atlas 0531 EU&IA potentiostat was used for performing the tests.

The impedance tests were carried out under corrosion potential. The voltage signal amplitude was equal to 10 mV, and the range of signal frequency changes amounted to  $100\text{ kHz} \div 0,1\text{ Hz}$ .

Corrosion process parameters were determined by using AtlasLab 2.0 and EIS Spectrum Analyser software.

For the tested object an equivalent model in the form of a substitute electric circuit was selected. Its schematic diagram is presented in Fig. 2.

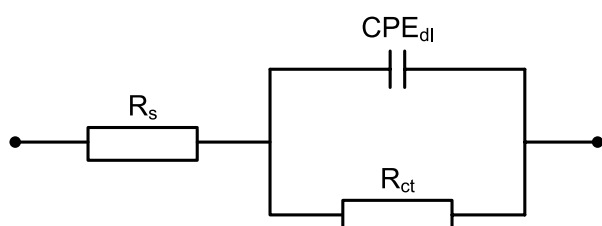


Fig. 2. The selected substitute circuit for corrosion system

In the selected circuit model the element  $R_s$  is equivalent to resistance of the electrolyte forming corrosion environment. And,  $R_{ct}$  characterizes resistance of charge transfer through metal-electrolyte border associated with metal oxidation process, and the constant phase capacity  $CPE_{dl}$  – capacity of double layer formed on the border of the considered phases [14].

For the selected substitute circuit the resultant impedance can be described by the following relation [6]:

$$Z = R_s + \frac{1}{\frac{1}{R_{ct}} + CPE_{dl}(j\omega)^{n_{dl}}} \quad (1)$$

## RESULTS OF THE TESTS

### STATIC TENSION TESTS

Tab. 3 shows results of the static tension tests conducted on the investigated alloys and their joints welded by using FSW method.

Tab. 3. Mechanical properties of 7020M and 7020 alloys and their FSW-welded joints

Specimen	$R_m$ [MPa]	$R_{p0,2}$ [MPa]	A [%]
7020M	443	397	9,8
7020M - FSW	437	393	10,2
7020	372	317	16,0
7020 - FSW	370	314	15,4

The mechanical properties of FSW-welded joints are almost the same as those of respective parent materials. This is proved by location of fracture which, in all the tested specimens, occurred in parent materials in the distance of about 10 mm apart from weld junction. In the case of friction welding, heat affected zone (HAZ) is very narrow, which may be concluded that the material in the place of fracture was unchanged, i.e. it remained parent. Fig. 3 shows image of an example FSW-welded specimen after static tension test.

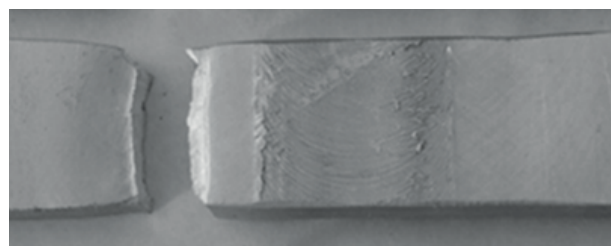


Fig. 3. Image of an example FSW-welded specimen after static tension test

### TESTS OF RESISTANCE TO ELECTROCHEMICAL CORROSION

The test results of electrochemical impedance spectroscopy (EIS) for the specimens made of parent material of 7020M and 7020 alloys and their FSW-welded joints, recorded during the tests, were analyzed by using EIS Spectrum Analyser software. As a result, were determined corrosion process parameters whose mean values based on five specimens are presented in

Tab. 4. The parameters determine particular components of the model, i.e. the substitute electric circuit selected in compliance with the applied testing method.

Tab. 4. Parameters of the substitute electric circuit for the corrosion system of 7020M and 7020 alloys and their joints welded by using FSW method

Specimen	$R_s$ [ $\Omega \cdot \text{cm}^2$ ]	$R_{ct}$ [ $\Omega \cdot \text{cm}^2$ ]	$\text{CPE}_{dl}$ [ $\mu\text{F}/\text{cm}^2$ ]	$n_{dl}$ [-]
7020M	0,28	1241,4	8,6	0,984
7020M - FSW	0,45	614,7	10,6	0,996
7020	0,42	773,01	29,13	0,941
7020 - FSW	0,66	524,55	21,02	0,965

In the case of AW-7020M alloy value of the resistance of charge transfer through double layer,  $R_{ct}$ , is twice smaller for the welded specimen than for the parent material, which indicates that charge transfer resistance between material and electrolyte is lower. Differences in  $R_{ct}$  - values recorded during testing the AW-7020 alloy and its FSW –welded joints were significantly lower ( by abt. 30 % ), and also the welded specimens revealed a lower value of the parameter in question.

The component of the capacity impedance power exponent  $n_{dl}$  for the substitute system, which determines homogeneity of corrosion process occurring on surfaces of the tested specimens, took similar high values (exceeding 0,9) for all the specimens. It shows an activating character of the constant-phase element  $\text{CPE}_{dl}$  in the conditions of the performed tests. The value of the component of capacity impedance power exponent close to or equal to 1 may show that during the tests uniform corrosion takes place or no diffusion limitations are present during the corrosion process.

The results of the impedance spectroscopy tests are also presented graphically on Nyquist's diagrams (Fig. 4 and 5), together with the relevant best-fit theoretical curves.

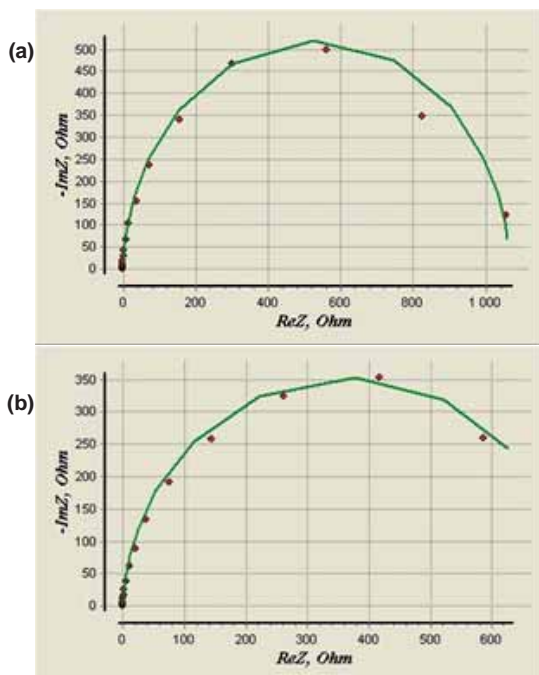


Fig. 4. Example Nyquist's diagram for: a) specimen of 7020M parent material ; b) FSW- welded specimen of 7020M alloy

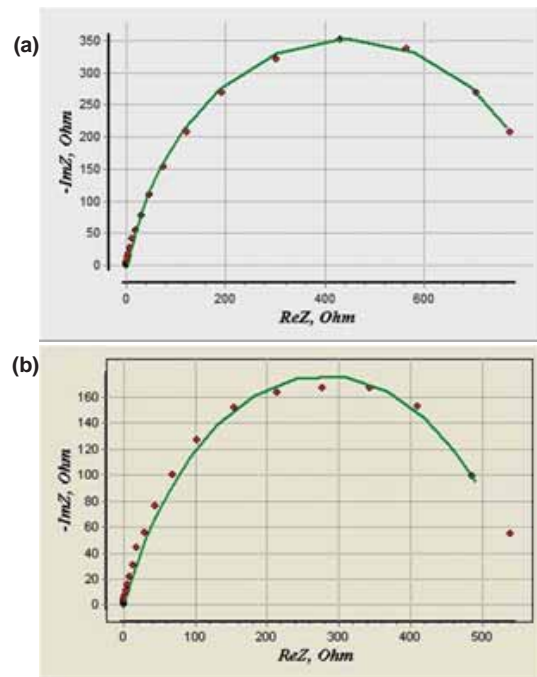


Fig. 5. Example Nyquist's diagram for: a) specimen of 7020 parent material; b) FSW- welded specimen of 7020 alloy

## SUMMARY AND CONCLUSIONS

The tests of mechanical properties of AW-7020 and AW-7020M alloys have shown that the alloy with the changed chemical composition reveals a higher strength and lower plasticity compared to the basic alloy (7020). For both the tested alloys the joints welded by using the friction stir welding method (FSW) probably show higher strength properties compared to their parent materials. This is proved by the fact that fracture occurred in the place 10 mm distant from the weld. Results of the strength properties recorded during static tension tests are on the same level.

An analysis of the data obtained from the impedance spectroscopy tests revealed that the FSW-welded specimens showed a lower resistance to electrochemical corrosion compared to those made of parent material, and a greater difference was recorded in the case of 7020M alloy.

For all the specimens it was stated that corrosion process is based on activating control.

In the case of AW-7020M alloy, the parameter  $R_{ct}$  (charge transfer resistance), the most important from the point of view of electrochemical corrosion resistance, obtains twice greater values for parent material specimen compared to that welded by using FSW method. For AW-7020 alloy the difference between the recorded  $R_{ct}$  values for parent material and FSW-welded joint reached value of about 30 % in favour of parent material.

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## BIBLIOGRAPHY

1. Bugłacki H., Nesor G.: Properties of welded Al-alloys applicable in shipbuilding (in Polish). Biuletyn Instytutu Spawalnictwa w Gliwicach (Bull. of Welding Institute, Gliwice), No. 5/2001.
2. Cudny K., Puchaczewski N.: Metal alloys for ship hull structures and ocean engineering objects ( in Polish). Wydawnictwo Politechniki Gdańskiej ( Publishing House of Gdańsk University of Technology), Gdańsk 1995.
3. Czechowski M.: Effect of anodic polarization on stress corrosion cracking of some aluminium alloys, *Advances in Materials Science*, Vol 7, pp. 13-20, number 1(11) 2007.
4. Czechowski M.: Low-cycle fatigue of friction stir welded Al-Mg alloys. *Journal of Materials Processing Technology*, 164-165(2005), pp. 1001÷1006.
5. Dudzik K., Czechowski M.: Analysis of possible shipbuilding application of Friction Stir Welding (FSW) method to joining elements made of AlZn5Mg1 alloy. *Polish Maritime Research* No.4/2009.
6. Dudzik K., Jurczak W.: Influence of friction stir welding on corrosion properties of AW-7020M alloy in sea water. *Advances in Materials Science*, Vol. 15, No. 1 (43), March 2015.
7. Ferraris S, Volpone L.M.: Aluminium alloys in third millennium shipbuilding: materials, technologies, perspectives, *The Fifth International Forum on Aluminium Ships*, Tokyo, 2005.
8. Jurczak W.: Problems and prospects of Al-alloys in their application to marine structures ( in Polish) . *Zeszyty naukowe Akademii Marynarki Wojennej ( Scientific bulletins of Polish Naval University )*, Vol. 41 , No. 4 (183) 2010, Gdynia 2010.
9. Jurczak W.: The effect of heat treatment on the structure and corrosion resistance of Al-Zn-Mg alloys. *Polish Maritime Research* , Vol. 15 , No.4(58)/2008.
10. Lahti K.: FSW – possibilities in shipbuilding, *Svetsaren, The ESAB Welding and Cutting Journal*, Vol. 58, No.1/2003.
11. Mazzolani F. M.: *Aluminium Alloy Structures* (second edition), E&FN SPON, an imprint of Chapman & Hall, London 1994.
12. Pietras A., Zadroga L., Łomozik M.: Characteristics of weld produced by using friction welding technique associated with mixing weld material (FSW) ( in Polish), *Biuletyn instytutu spawalnictwa w Gliwicach ( Bul. of Welding Institute , Gliwice)*, No.3/2003.
13. Sharma C., Dwivedi D. K., Kumar P.: Effect of welding parameters on microstructure and mechanical properties of friction stir welded joints of AA7039 aluminum alloy. *Materials and Design*, 36 (2012).
14. Trzaska M., Trzaska Z.: Electrochemical impedance spectroscopy in material engineering ( in Polish). *Oficyna Wydawnicza Politechniki Warszawskiej (Publishing House of Warsaw University of Technology)*, Warsaw, 2010.
15. ASTM G 3 Standard Practice for Conventions Applicable to Electrochemical Measurements in Corrosion Testing. ?
16. ASTM G 106 Standard Practice for Verification of Algorithm and Equipment for Electrochemical Impedance Measurements.

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