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The Mechanism of Solid State Joining THA with AlMg3Mn Alloy

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Abstract

The results of experimental study of solid state joining of tungsten heavy alloy (THA) with AlMg3Mn alloy are presented. The aim of these investigations was to study the mechanism of joining two extremely different materials used for military applications. The continuous rotary friction welding method was used in the experiment. The parameters of friction welding process i.e. friction load and friction time in whole studies were changed in the range 10 to 30kN and 0,5 to 10s respectively while forging load and time were constant and equals 50kN and 5s. The results presented here concerns only a small part whole studies which were described elsewhere. These are focused on the mechanism of joining which can be adhesive or diffusion controlled. The experiment included macro- and microstructure observations which were supplemented with SEM investigations. The goal of the last one was to reveal the character of fracture surface after tensile test and to looking for anticipated diffusion of aluminum into THA matrix. The results showed that joining of THA with AlMg2Mn alloy has mainly adhesive character, although the diffusion cannot be excluded.

Keywords: Friction welding, Tungsten heavy alloys, Aluminum alloys, Structure, Properties

1. Introduction

Friction welding is the solid state joining method in which bonding forms at temperatures lower than the melting point of the metal with the lowest melting temperature. According to American Welding Society (AWS) friction welding is the process that produces a weld under compressive force contact of joined pieces rotating or moving relative to one another to create heat and plastically displace materials from the faying surfaces. This is very simple and time saving method which in many cases make possible to produce defect free, high strength parts like some automobile components, pump shafts, cutting tools and many others. As was said before, the method is simple so it is widely used in industry. It is true only in case when the mechanical and physical properties of joined pieces are the same or very close. The process becomes more and more complicated if materials to be joined differ each from the other [1-2]. Many highly efficient solid-state joining processes such as explosion, friction, diffusion, and cold roll welding are being developed to join dissimilar materials. Among these welding techniques, rotary friction welding (RFW) technique is one of the best methods to join dissimilar metals due to its characteristics of high reproducibility, sub-melting temperature, short weld time, low energy input and almost negligible intermetallic formation [3−4]. The problems are still meeting when the heat generated during friction welding starts the processes of precipitation of hard and brittle particles at the interface. This makes the joining brittle which in turn decrease the strength of joining. Another problem appear in case of cast iron joining, where the graphite existing in the interface works as specific lubricant, decreasing the friction coefficient protecting against the heat generation enough for joining during upsetting stage. As stated Winiczenko at all [5-7] the graphite in ductile iron play also one more role forming thin layer between joined pieces consisted with parallel basal {0001} type planes oriented perpendicular to the axis of joined pieces. The last problem can be overcome using interlayer which can work as sinks for carbon atoms [8]. A large number of references on the RFW of dissimilar metals have indicated that the relations between the bond strength and the microstructure at the interface have been established extensively [9-11].

The purpose of this paper is to present the results concerning possibility of diffusion during friction welding of tungsten heavy alloy with AlMg3Mn alloy

2. Experimental procedure

The commercial AlMg3Mn alloy and tungsten heavy alloy containing 98%W produced using liquid phase sintering (LPS) method (fig.1) were used in experiment.

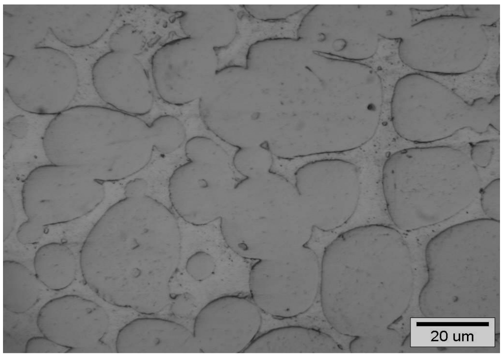


Fig. 1. The microstructure of THA used in experiment

The specimens used in experiment were bars with diameter of 20mm. The working surfaces were machined before friction welding. All welds were produced using a continuous-driving machine. The parameters of friction welding were as follows: the friction load 12,5kN and friction time 4,5 and 9,5s. The forging load and time were 50kN and 5 s respectively. The rotational speed was constant held at 1400 r/min.

From joined pieces the specimens for metallography and microanalysis with plane perpendicular to joining interface were cut. The specimens for macro- ad microstructure observations and chemical microanalysis were grinded and polished conventionally using standard method but not etched. Fracture surfaces obtained after tensile tests were observed in Zeiss scanning electron microscope equipped with EDS attachment.

It follows from table 1 that the strength of joined specimens depends on friction welding parameters and the best results were obtained for friction load and time 22,5 kN and 9,5 s respectively. It should be noted that the strength of the joining between tungsten heavy alloy and aluminum alloy is higher than yield stress of AlMg3Mn alloy.

3. Results

3.1. Mechanical testing

The friction welded specimens were tensile tested to evaluate strength of the joining. The results of these measurements are given in table 1.

Table 1.
The mean tensile strength of joined specimens

Friction load [kN]	Friction time [s]	Tensile strength [MPa]
12,5	4,5	130
	9,5	170
25,0	4,5	156
	9,5	196

The last statement was evidenced by straight lines visible of the free surface of tensile tested aluminum (fig.2). There is no question that these lines are steps caused by many dislocations emerging from inside of the specimen when sliding in glide systems.

a)

b)

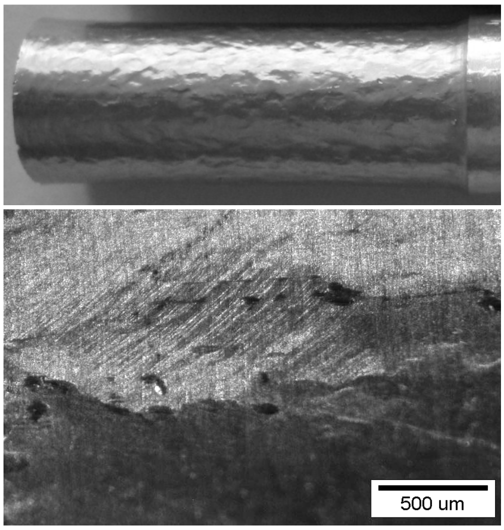


Fig. 2. The view of the surface of aluminum part after tensile testing of friction welded THA with AlMg3Mn alloy: a – surface deformation caused by grain rotation, b – parallel lines on the surface representing steps formed with dislocation lines emerging from inside when sliding in glide systems

3.1. Macro- and microstructure observations

The microstructure of the aluminum alloy immediate to joining plane is show in fig.3. Relative thin layer thickness of approximately 750 μm is visible in micrographs.

a)

b)

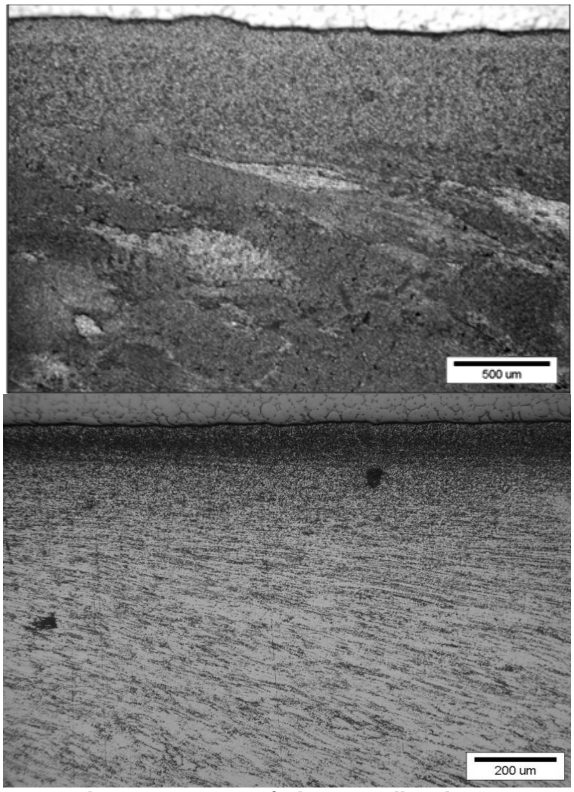


Fig. 3.The macrostructure of AlMg3Mn alloy close to joining interface friction welded at friction load 12,5kN and friction time: a–4,5s and b–9,5s

The layer consists of very fine grains which were difficult to resolve, probably because of extremely deformation causing high density severe and deep etching of the surface. The example of microstructure of the layer adjacent to the friction plane is given in fig.4. It looks from the micrograph (fig.4) that the grains are very small and their diameter is the order of 10μm or even less.

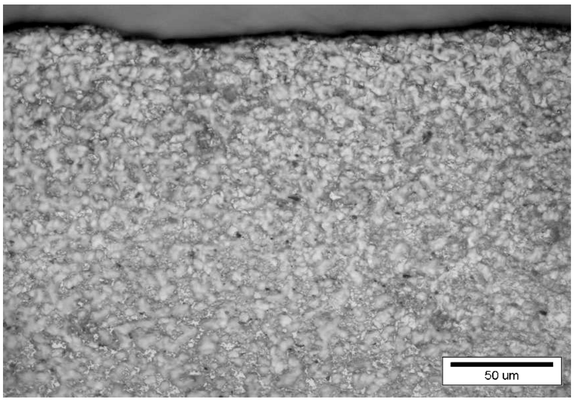


Fig. 4. The microstructure of AlMg3Mn alloy close to joining interface after friction welding at friction load 12,5kN and friction time 9,5 s

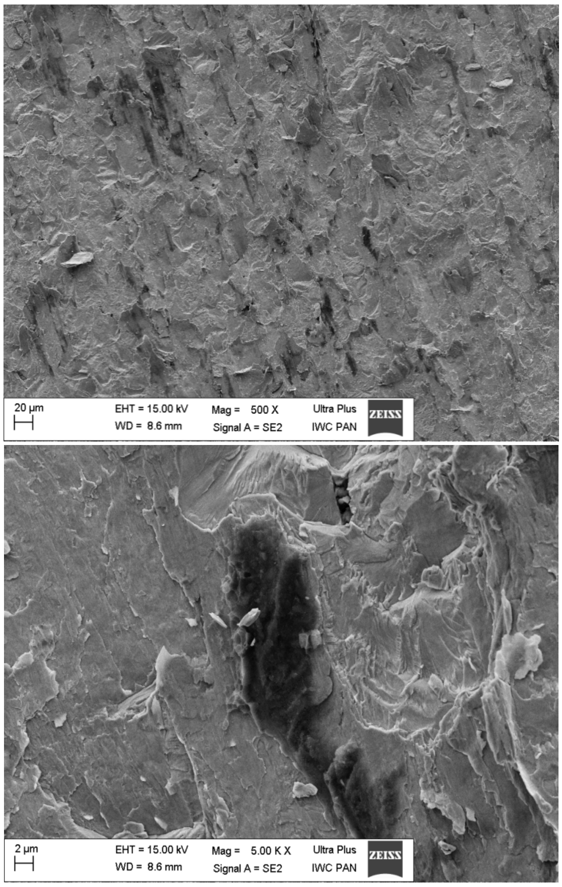
3.2. SEM observations

The SEM observations were carried out on both surfaces: aluminum and THA, formed while fractured in tensile test. Fig. 5 presents the example of fracture surface morphology of the pieces joined at friction load and time 12,5kN and 9,5s.

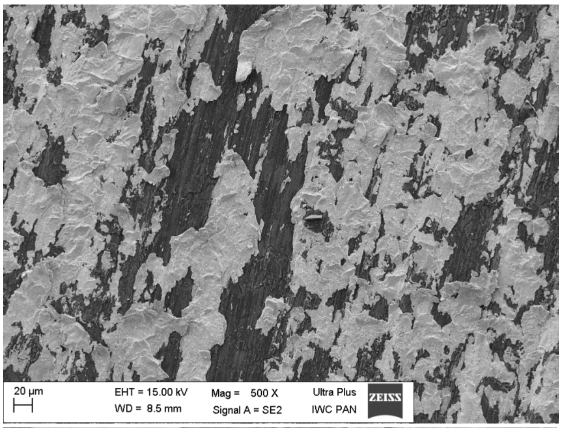
In the micrograph taken at relative small magnification (Fig. 5a and b) the characteristic circular marks are visible on both pieces broken in tensile test. In fig.5a and b we can see fracture surface from side of tungsten heavy alloy which is very rough and where mainly fractured tungsten grains are visible. At higher magnification brittle fracture mode proceeding throughout cleavage planes of tungsten grains can be observed (Fig. 5b). On fracture surface visible on aluminum alloy side, many parts of fractured tungsten grains can be very easy identified. They are white in color (Fig. 5c,d) and must be very strong connected with aluminum substrate. The proof is the fact that the fracture proceeds throughout the tungsten grains which means that adhesion between tungsten grains and aluminum was stronger than resolving strength in cleavage planes of tungsten grains.

a)

b)



c)



d)

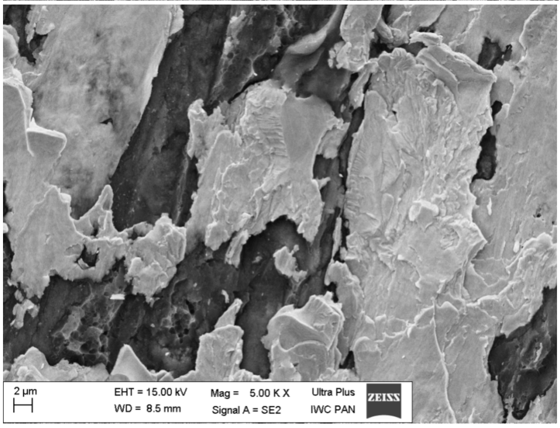


Fig. 5. The morphology of fracture surface of the specimen joined at friction load 9,5kN and time 9,5 s: a-b – on the THA side and c-d – on the aluminum alloy side

3.3. EDS microanalysis

In fig.6 the examples of EDS results are depicted. The first three micrographs shows the places from where the information on chemical were taken and the forth one of the EDS spectrum. The selected quantitative results of chemical analysis obtained in these three points were collected in table 2.

Table 2a.
The results of EDS measurements (fig.6a)

Element	Series	unn. C [wt. %]	norm. C [wt. %]	Atom. C [at. %]	Error (1 sigma)
Ni	K-series	52,29	51,09	60,32	1,69
W	L-series	28,05	27,41	10,33	1,18
Fe	K-series	12,98	12,68	15,74	0,44
Co	K-series	4,08	3,98	4,68	0,19
Al	**K-series**	**1,22**	**1,19**	**3,06**	0,09

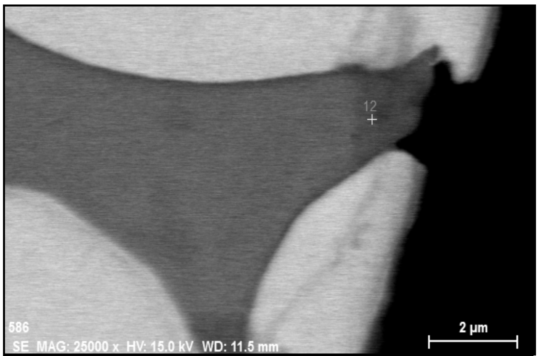
Table 2b.
The results of EDS measurements (fig.6b)

Element	Series	unn. C [wt. %]	norm. C [wt. %]	Atom. C [at. %]	Error (1 sigma)
Ni	K-series	52,40	52,47	65,18	1,70
W	L-series	30,15	30,19	11,97	1,27
Fe	K-series	12,07	12,09	15,78	0,42
Co	K-series	4,09	4,09	5,06	0,05
Al	**K-series**	**0,34**	**0,34**	**0,91**	0,07

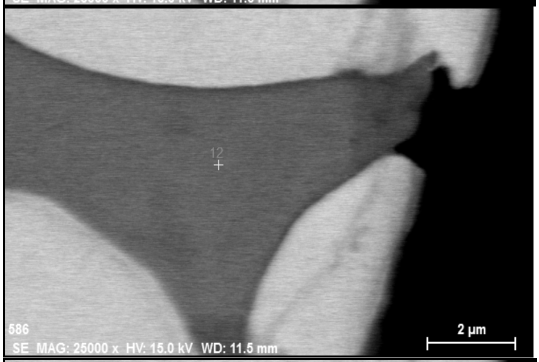
Table 2c.
The results of EDS measurements (fig.6c)

Element	Series	unn. C [wt. %]	norm. C [wt. %]	Atom. C [at. %]	Error (1 sigma)
Ni	K-series	52,80	47,60	40,78	1,69
W	L-series	30,21	27,24	7,45	1,22
Fe	K-series	12,54	11,31	10,18	0,42
Co	K-series	4,43	3,99	3,41	0,20
Al	**K-series**	**0,11**	**0,10**	**0,18**	0,04

a)



b)



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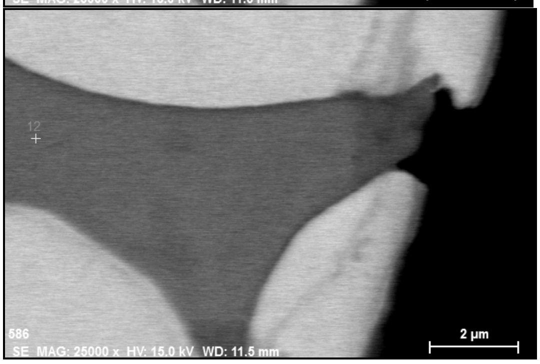

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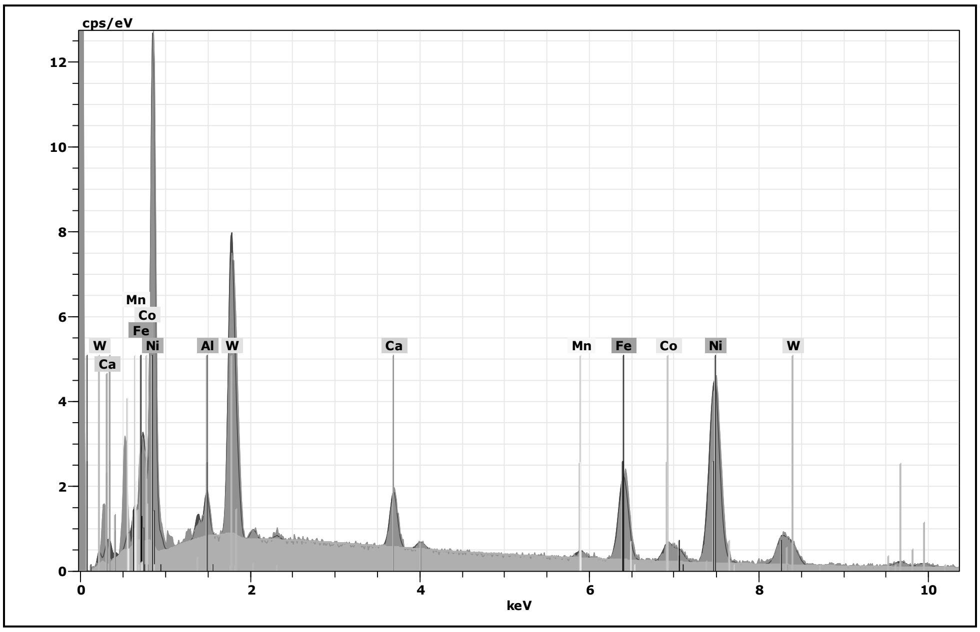

Fig. 6. The results of EDS measurements: (a-c) - the micrographs shoving the places where the chemical microanalysis was done, d – example of EDS spectrum

Compare the results given in table 2, especially for aluminum content in nickel it is visible that its concentration is the highest at place located very close to the joining interface and decrease with increase of the distance from it. It may suggest the diffusion of aluminum into the nickel-base of tungsten heavy alloy.

4. Discussion

In introduction it was stated that the friction welding is very simple and effective method for joining many material. The exceptions are so called different material joining of which supply many problems. It would be interesting to explain what is understood as "different" material? The answer we can find during literature review where even different grade aluminum alloys or different grade steels are treated as different? So before starting the analysis the authors decided to bring the selected properties of the materials used in this experiment (table 3).

Table 3.
Selected properties of tungsten and aluminum

Property	W	Al
Melting point ^{o}C]	3420	660
Density [Mg/m^3]	2,7	19,25
Young modulus [GPa]	411	70
Thermal expansion coefficient [$10^{-6}\cdot K^{-1}$]	4,5	23,1
Brinell Hardness [MPa]	2570	245

It follows from the table 3 that tungsten and aluminum are extremely different. The melting points differ more than four times, Young modulus almost and density more than six times. The density of tungsten is ten times over aluminum density while coefficient of thermal expansion of tungsten is 6 times lower than aluminum. Looking on these differences it would be very easy to anticipate the difficulties which can arise during friction welding tungsten with aluminum alloy. However, it should be remembered that in experiment we don't used pure tungsten but its alloy, where tungsten grains were embedded in Ni-base matrix obtained by liquid sintering. The melting point of this alloy and more accurate the Ni matrix was approximately 1500^{o}C. This makes the problem of joining a little easier but still difficult. Despite of the problems caused by huge differences between friction welded materials it was possible to produce high quality joints with strength comparable and even higher than the yield strength of AlMg3Mn alloy. As follows from SEM observations, the high quality connections forms between joined pieces. The evidence is the morphology of fracture surface where in many places cleavage planes in tungsten grains are clear visible. It means that the strength of the joint must exceed the strength of tungsten in cleavage planes. The question is what is the mechanism of joining process? The result of EDS studies, example of which was given in fig.6 and table 2 shows that there is some diffusion aluminum into Ni-base matrix. This might be a little surprising if concern short time of the process, although Zimmerman at all discovered diffusion of aluminum atoms in Al_2O_3 ceramic during friction welding in time of second [12]. However it seems to us, that even if diffusion is involved in joining of THA with AlMg3Mn alloy, its role is probably not deciding. One of the reasons is that it concerns Ni-base matrix only and no diffusion was discovered from aluminum alloy into tungsten grains. The proportion of matrix versus tungsten grains is 10% only so it looks that the diffusion plays a minor role in forming joining between THA and AlMg3Mn alloy. If so, the authors believe that adhesion is most responsible for producing high strength joint between tungsten heavy alloy and AlMg3Mn alloy.

5. Conclusions

On the basis of the experimental results including mechanical testing, structure observations, SEM investigations and EDS microanalysis the following conclusions can be proposed:

1. The rotary friction welding is appropriate method for producing high strength joint between tungsten heavy alloy and AlMg3Mn alloy.
2. The strength of the joining depends on load during friction and time of the process.
3. The strength of friction welded THA and AlMg3Mn alloy is comparable or even higher than yield strength of aluminum alloy.
4. In author's opinion the joining formed between tungsten heavy alloy and AlMg3Mn alloy has mainly adhesive character, although diffusion of aluminum into Ni-base matrix can't be excluded.

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