Зварювання тертям з перемішуванням (ЗТП) є одним з методів механічного з'єднання, що не потребує присадочного металу. Тепло отримують від сили тертя між основним металом і інструментом тертя. ЗТП запропоноване Інститутом Зварювання (ІС) в 1991 році, яке, як очікується, дозволить подолати складнощі при зварюванні металів з низькою зварюваністю. Параметри ЗТП визначають якість з'єднання, і в даній роботі нормальна сила як незалежний параметр варіювалася на рівні 13000, 14000 та 15000 Н. Швидкість обертання і подачі регулюється на 1092 об/хв та 200 мм/хв відповідно. З експериментальних результатів встановлено, що найбільш міцне з'єднання забезпечується при 15000 Н (зразок 1). Стверджувалося, що краща якість з'єднання виходить за найвищої теплової потужності. Висока теплова потужність забезпечує достатню зварну точку і час для росту зерен алюмінію, що, в свою чергу, збільшує межу міцності з'єднання, отриманого ЗТП.

Однак з середніх значень і лінії тренду можна припустити, що велика сила тиску завжди призводить до більш високої межі міцності. Межі міцності були майже на одному рівні (115,44 ± 1,56 МПа), в той час як розрахункова теплова потужність лінійно залежна від сили тиску: 73,59, 79,25 та 84,91 Дж/мм для сил тиску, рівних 13000, 14000 та 15000 відповідно. Зафіксована температура, яка вказує на тепловую потужність, показала ту ж тенденцію з межею міцності, вона перебувала на тому ж рівні: 491,55 ± 2,22 °С. Напевно деякі аспекти не були враховані в математичній моделі теплової потужності. Або, можливо, припущення про більш високу теплову потужність не завжди досягається за більш високої сили тиску. На підставі літературних даних встановлено, що межа плинності знижується при більш високій температурі. Більш низька межа плинності зменшує силу тертя при постійній нормальній силі, що, в свою чергу, призводить до зниження теплової потужності, що суперечить попередньому припущенню.

Інша література, яка розглядає коефіцієнт тертя як функцію температури, показала, що коефіцієнт змінюється через температуру.

І, нарешті, більш висока нормальна сила не означає, що міцніше з'єднання може бути отримане за допомогою зварювання тертям з перемішуванням.

Ключові слова: зварювання тертям з перемішуванням, нормальна сила, сила тертя, коефіцієнт тертя, межа міцності

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CONTROLLING THE PRESSURE FORCE TO OBTAIN A BETTER QUALITY OF ALUMINUM 6061 FRICTION STIR WELDED JOINT

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1. Introduction

The patent of FSW is held by Wayne Thomas under the Welding Institute institution – England in 1991 [1]. The FSW is a solid state join method and has the ability to be applied at materials with low ability in the sense of conventional welding. The highest temperature in the welded region is designed to be 80 % to 90 % of the melting point of the workpiece. By the name, the heat of the FSW is obtained from the friction force between the friction tool and base metal with 95 % heat obtained from friction between the tool shoulder and workpiece, 3 % from the pin and nugget zone and 2 % due to the strain rate energy conversion. The resulted heat has significant effects on the joint quality, residual stress, distortion and the lifetime of the tool [2]. Too high temperature is softening the workpiece and causes slip [3]. There are many aspects that should be evaluated, to obtain good friction welded joints.

2. Literature review and problem statement

The parameters involved in the FSW process such as rotational speed, travel speed, downward force (also called as pressure or normal forces), lateral force, tools inclined angle, shoulder plunge and probe penetration determine the quality of resulted joints. Downward force is the pressure force given to the tool and transmitted to the workpiece to keep the contact between the friction tool and base metal that control the penetration and heat level while the process is ongoing [4]. Forces, which are assumed to determine the joint quality should be controlled [5]. In the paper, the three-axis forces

were close loop controlled using a dynamometer. The independent parameters of the FSW process are altered. Those are traverse speed, rotation speed and plunge depth.

The effect of pressure force on the tensile strength of stir welded magnesium AZ61A has been studied [6]. The pressure forces are varied in 5 combinations: 3, 4, 5, 6, 7 kN. Tensile strength, microstructure and hardness were evaluated and it was shown that the 5 kN pressure force produced the highest tensile strength linearly with the grain size and hardness in the stir zone.

From the literature review, the awareness to control normal forces has been originated. However, in [5] the normal force was only as a controlled condition, not as an independent variable which was resulted from varied three independent variables: traverse speed, rotation speed and plunge depth. Whilst, in [6] the pressure force has been already varied to obtain the relation between pressure force and tensile strength of the joint. It was found that the higher pressure force did not mean a stronger joint. It was claimed that the reason for the phenomenon is the formed grain structures and hardness of the joint. We consider that the grain structures and hardness also the other results of the varied normal forces which may coincide with the tensile strength. There is a reason to think that pressure force is needed to control the friction force. This friction force in turn actuates the heat input that finally determines the grain structures, hardness and tensile strength which may confirm each other.

The higher the pressure force, the higher the friction force that in turn increased the resulted heat. With higher pressure force which means higher inputted heat to the workpiece, it is hoped that the higher tensile strength of the joint will be obtained. Based on the analysis of conventional welding (Gas Metal Arc Welding – GMAW), the inputted heat determines the temperature history of a certain position. As it is well known, the temperature history has wide consequences such as developed microstructures which in turn determine the mechanical properties of the resulted joint [7]. As shown in [7], not only the magnitude of the heat input, which significantly affects the temperature history, but the temperature histories are also governed by the variation of electric current and welding speed. It means, although the heat input is equal, the temperature history will be altered due to different electric currents. Based on the conventional welding practice, the heat input is the key factor that determines the produced tensile strength.

In this paper, the effect of pressure force when FSW was applied to the aluminum 6061 instead of magnesium is studied. The aluminum 6061 is considered as the future promising metal due to its high strength to weight ratio. The final quality of the weld joint is represented by its joint tensile strength since the tensile test provides the entire joint properties instead of local properties such as hardness or microstructure. The normal force determines the friction force which in turn drives the heat input. The expected heat input can be calculated using simple equations. The actual heat input in the FSW process is indicated by the temperature at a certain position, thus it is something to measure the temperature to evaluate the actual heat input of the process. Both the calculated and actual heat inputs then can be compared. The analysis will be carried out to evaluate the resulted tensile strength to the theoretical and the actual heat input to find out and understand the actual phenomenon developed in the FSW process.

3. The aim and objectives of the study

The aim of the study is obtaining a stronger friction welded joint by providing the controlled normal force of the friction tool.

To achieve this aim, the following objectives are accomplished:

– performing the tensile test for the specimen with varied normal force;

– measuring the real temperature at a certain relative position to the friction tool;

– correlating the resulted tensile strength to the yielded temperature and normal force.

4. Experiment procedure for varied pressure force

This paper used *the true experimental method* with an independent variable which is pressure force. The pressure force varies at 13,000, 14,000 and 15,000 N. The other parameters such as rotational and travel speeds are maintained to be constant: 1,095 RPM and 200 mm/min respectively. The tensile test was applied at resulted joints. The friction welding process was carried out at the X6328B universal milling machine using a special jig with spiral springs to control the pressure force as shown in Fig. 1. As it has been mentioned, the specimen is an aluminum 6061, which has better weldability compared to the other class of aluminum, good formability when they are extruded, good corrosion resilience and high strength to weight ratio. The composition and mechanical properties of the aluminum are shown in Tables 1, 2 respectively. The raw material to be stir-welded is a 140×70 mm rectangle of the plate with a thickness equal to 3 mm. The HQ 760 steel was used as a friction tool with the shoulder and pin diameters of 15 mm and 7 mm respectively as shown in Fig. 2. also gives a table to describe the parameters of the friction tool. The pin was tapered to obtain optimum mass transfer and the normalizing heat treatment was applied to obtain adequate hardness of the friction tool especially at the friction surfaces.

From the joined plate, the tensile specimen was formed following the ASTM E8 standard as shown in Fig. 3.

The tensile test was applied at a universal testing machine as shown in Fig. 4. The major result of the tensile test is the ultimate tensile strength of the joints.

Fig. 1. X6328B Krisbow universal milling machine

Table 1

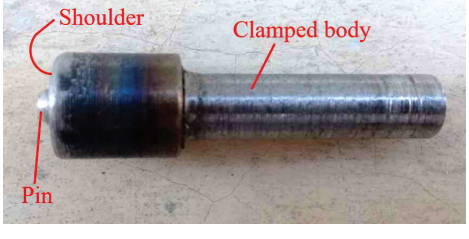
Composition of Aluminum 6061

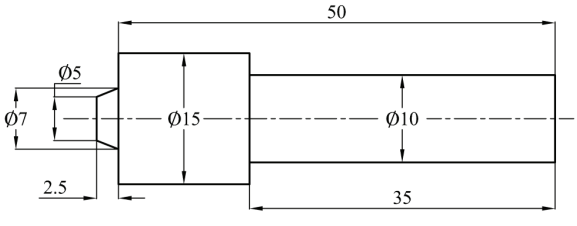
Composition	Al	Mg	Si	Fe	Zn
Content % weight	95.8–98.6	0.8–1.2	0.4–0.8	Max 0.70	Max 0.25
Composition	Cu	Cr	Ti	Mn	Others
Content % weight	Max 0.40	Max 0.35	Max 0.15	Max 0.15	Max 15

Table 2

Mechanical properties of Aluminum 6061

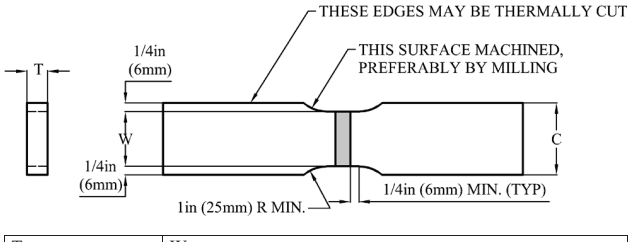
Properties	Values	Properties	Values
Tensile strength	12.6 (kg/mm^2)	Shear strength	8.4 (kg/mm^2)
Yield strength	5.6 (kg/mm^2)	Hardness	30 BHN
Elongation	30 %	Fatigue limit	6.3 (kg/mm^2)





Parameters	Values
Shoulder diameter	15 mm
Pin diameter	7 mm
D/d ratio	2.14
Pin length	2.5mm
Pin geometry	Tapered
Materials	HQ 760 steels
Composition	C: 0.42 – 0.50; Cr, Ni, Mo: Max 0.63, Mn: 0.50 – 0.80; Si: 0.40; S: 0.020 – 0.045

Fig. 2. Friction tool, camera shoot and technical drawing



T	W
<1 in (25 mm)	1.50 in ±0.01 mm (38±0.25 mm)
≥1 in (25 mm)	1.00 in ±0.01 mm (25±0.25 mm)

Fig. 3. Tensile specimen

Fig. 4. Universal tensile machine

While the FSW process is ongoing, the temperature of a node with a certain position relative to the friction tool was measured using an infrared thermometer as shown in Fig. 5.

Fig. 5. Infrared thermometer

The results obtained from the experiment and calculation are described in the next section (section 5).

5. Results of the experiment

The result of the experimental method is listed in Table 3. The main result is the ultimate tensile strength for each repetition and the average for certain treatments. The temperature for a certain relative position and their average are also embedded for each repetition. Heat input based on the calculation using equation (1) is shown for each pressure force which is expressed as a graph as shown in Fig. 6. Heat input is heat embedded in the base metal due to the friction force between the friction tool and base metal. Heat input expresses the heat transferred to the base metal for a certain length and can be calculated based on equation (1). Heat input has been proved to determine weld quality in conventional welding (GMAW) [7].

$$Q' = \frac{\mu F_N (R_i + R_o)\omega}{2v_f}, \quad (1)$$

where Q is heat input (J/mm), μ is coefficient of friction, F_N is pressure force (N), R_i is pin diameter (mm) and R_o is shoulder diameter, ω is the rotational speed (rad/sec) and v_f is feeding speed (mm/s). As can be seen in Fig. 7, based on the equation (1) the heat input increased linearly according to the pressure force which is hoped to improve the welding strength.

Table 3

Experimental results for varied pressure force

No	F_N (N)	σ_u (MPa)	σ_{avg} (MPa)	T (°C)	T_{avg} (°C)
1	13000	93	115.00	557	489.33
		112		478	
		140		433	
2	14000	80	117.00	542	492.33
		131		517	
		140		418	
3	15000	159	114.33	420	493
		104		486	
		80		573	

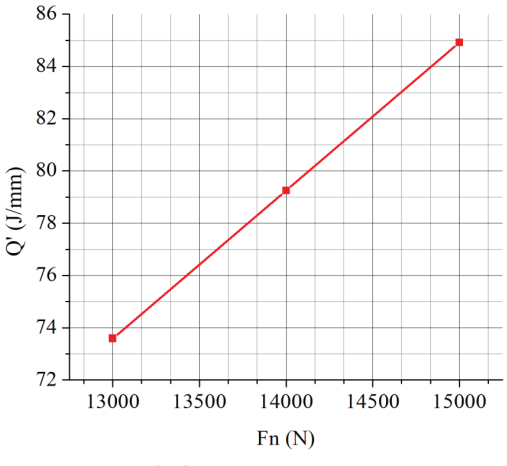


Fig. 6. Calculated heat input

The obtained tensile strength in MPa which is obtained from the experiment is shown in Fig. 7. Three data were extracted from each treatment and the trend line was made based on the mean data. Although the maximum tensile strength (159 MPa) was obtained from the 15,000 N pressure force (specimen 1), but based on the average values it cannot be said the 15,000 N pressure force produced the strongest joint.

Comparing Fig. 6, 7 it can be concluded that there are differences between the previous hypotheses that the increased pressure force which is hoped to increase the calculated heat input will increase the tensile strength. For this reason, the third data which is the temperature of nodes at a certain position relative to the friction tool was considered. The data were listed in Table 3 and shown graphically in Fig. 8. Evaluating Fig. 6–8, it can be said that Fig. 7, 8 confirmed each other. It should be noted that both of them (Fig. 7, 8) are obtained from the experiment method and Fig. 6 is calculated based on a theoretical approach, thus there must be aspects that were not considered in the theoretical approach.

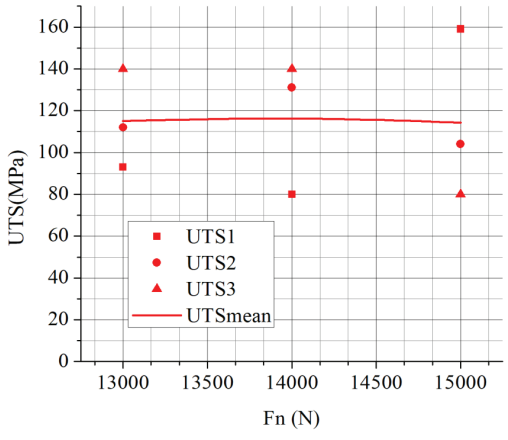


Fig. 7. Tensile strength for varied pressure forces F_N (N)

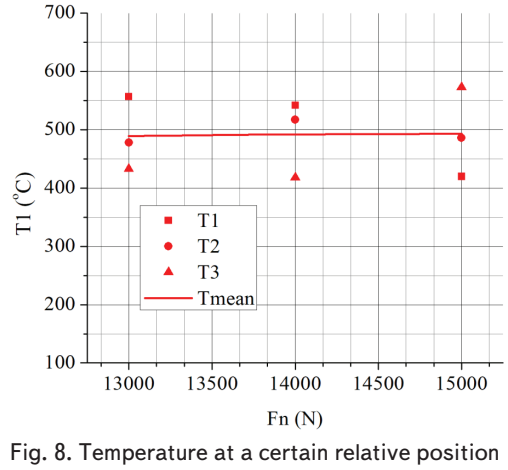


Fig. 8. Temperature at a certain relative position

Discussion is performed based on the experiment and calculation results, considering the developed initial assumption as will be discussed in the next section.

6. Discussion based on the experiment results

It was expected that with the higher normal force the heat input based on equation (1) would be increased and in turn the stronger joint will be obtained. This expectation was not confirmed by the mean values of tensile strength.

Some literature study was carried out to find important aspects that were not included in the equation (1). There is a good reference that provides the aluminum properties at elevated temperature [8] as shown in Fig. 9. From [8], as shown in Fig. 9, it can be concluded that the stress-strain curves, especially yield strength altered with the elevated temperature. This yield strength is an important aspect that determines the normal force for a certain strain (plunge depth in case of FSW) or reversely determines the strain for a certain normal force. But on the other hand, the temperature field is determined by the friction force and consequently the normal forces. This coupled analysis certainly cannot be represented by a simple equation as in equation (1) and maybe the numerical method is the only way to obtain better approaches [9]. In [9], a coupled Thermo-Metallurgy-Mechanical analysis was performed and the melted material was modeled by removing its stiffness and remaining plastic strain.

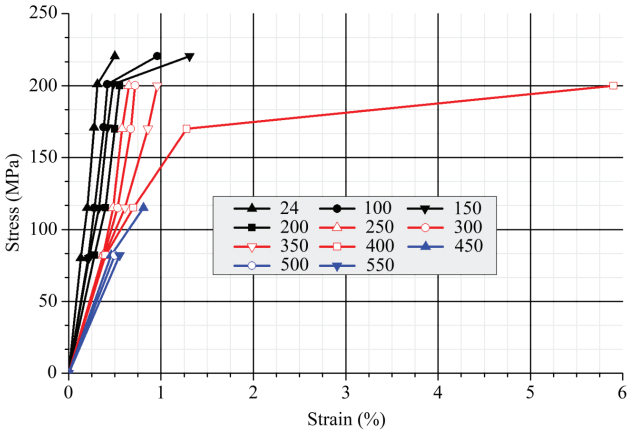


Fig. 9. Stress-strain diagram for AL6061 at elevated temperatures [8]

Coefficient of friction m also may change at a varied temperature. There is a paper that evaluated the effect of temperature on the coefficient of friction [10]. In [10], three ball friction apparatus was used, and a disk specimen was placed in a chamber in which temperature can be adjusted. In short, the friction coefficient, which is affected by temperature is shown in Fig. 10. Although the data are for 9Cr18Mo martensitic steels, but it is plausible to assume that the friction coefficient of AL6061 must be affected by the temperature at which it is more complicated to make the analysis.

Since the coefficient of friction and the strength of material which are altered due to temperature were not taken into account in the equation (1), and the heat input in Fig. 6 based on equation (1), the trend of tensile strength does not follow the calculated heat input.

The next research using numerical accession may be a good one since the simple analytic approach using equation (1) resulted in the deviated tensile strength to the measured one. Involving two proposed aspects, those are temperature dependence of tensile strength and coefficient of friction, in the numerical analysis is believed to involve coupled complex analysis which needs a deep element model based on comprehensive basic data. However, the numerical analysis proved to provide good results for a Coupled Thermo-Metallurgy-Mechanical phenomenon in the conventional welding process, especially Gas Metal Arc Welding – GMAW.

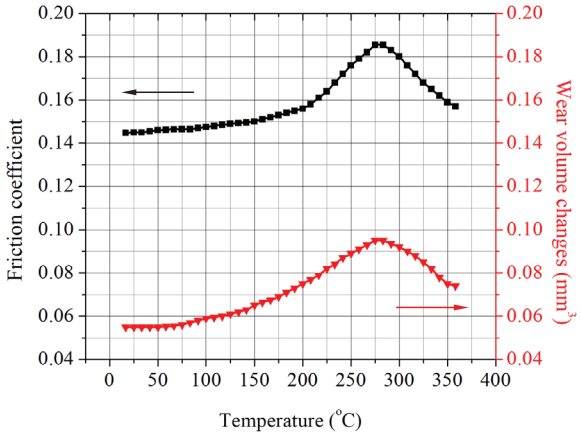


Fig. 10. Coefficient of friction for varied temperature [10]

7. Conclusions

1. The pressure forces of 13 kN, 14 kN and 15 kN produce tensile strength equal to 115 MPa, 117 MPa and 114.33 MPa respectively.

2. The temperatures at the certain relative position of the friction tool for the pressure force: 13 kN, 14 kN and 15 kN are 489.33 °C, 492.33 °C and 493 °C.

3. The tensile strength has the same trend values to the temperature, but differs with the calculated heat input. The reason for the deviation are aspects that were not included in the equation (1). At least two aspects can be proposed as reasons, those are altered strength of base metals and existing friction force when the temperature changes.

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