Experimental Investigation on Process Parameters of Dissimilar Double-Layered Wire Produced by Modified Friction Stir Extrusion Process

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Abstract: In this paper, a new production method of aluminium/steel double-layered wire is proposed using a modified friction stir extrusion process. The core and coating were made of St37 steel and aluminium alloy, respectively. For extruded specimens, the effects of the main process parameters including tool rotational speed and feed rate were investigated on adhesion strength and surface cracks. The tool rotational speed was studied at two levels of 300 and 600 rpm, and the feed rate at two levels of 4 and 12 mm/min. Pull-out test was carried out using a tensile test machine to evaluate the adhesion strength. Surface cracks were evaluated by the liquid penetrant test. The results suggest that the modified friction stir extrusion process can be used successfully to produce dissimilar double-layered wires. With the right combination of tool rotational speed and feed rate levels, a dissimilar double-layered wire can be produced with a high adhesion strength and good surface quality. No cracks were observed in specimens produced with the feed rate of 12 mm/min and rotational speed of 600 rpm. The maximum adhesion strength was 2867.13 N that was achieved with a tool rotational speed of 300 rpm and feed rate of 12 mm/min.

Keywords: Adhesion Strength, Crack, Double-Layered Wire, Friction Stir Extrusion, Liquid Penetrant Testing

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1 INTRODUCTION

Friction stir extrusion is a new process that could be used in the recycling of metal chips and refining the microstructure of materials. This process causes Severe Plastic Deformation (SPD) in the extruded part. The SPD processes have been used for two decades to modify the structure of materials [1]. One of the most important advantages of this method is the possibility of using chips and waste of other machining processes, which creates a lot of added value. In this method, the raw material is placed inside the die. The rotating plunger enters the die, and the friction between the plunger and the raw material leads to severe plastic deformation and production of the product.

The movement direction of the plunger in friction stir extrusion is opposite to the direction of the output product like in backward extrusion. This process is a solid-state forming method. The friction stir extrusion process is divided into two categories of wire and tube production [2]. The production of bilayer tubes consisting of an outer aluminium foam pipe and a dense inner aluminium pipe was studied by Hangai et al. [1] using friction stir back extrusion process. They produced the bilayer tubes consisting of an ADC12 foam outer tube and an AA1070 aluminium inner tube.

Baffari et al. [3] investigated the effect of process parameters for the flawless production of magnesium wire using the friction stir extrusion method. They compared the tensile strength of the samples obtained by this method with the primary prototypes. The numerical model was simulated with Deform software which was used to predict the temperature and strain distribution as well as material flow. The studied parameters were rotational speed, extrusion force, and extrusion ratio (each with three levels). They used tensile and macrographic tests to examine the specimens. Baffari et al. [4] presented the results of an experimental study on the friction stir extrusion process of AA2024 aluminium alloy chips with the aim of producing a metal matrix composite by adding silicon carbide powder. They added different amounts of SiC powder to recyclable aluminium chips.

Numerical simulations had been used to study the flow of material during the process. Buffa et al. [5] experimentally investigated the friction stir extrusion to recycle AZ31 magnesium alloy. They obtained tensile strength of up to 80% of the raw material with the best combination of parameters. By studying the specimens, they pointed to a three-dimensional helical flow in the samples during the process. They also studied the mechanical properties of extruded wires in terms of stiffness and ultimate tensile strength. Tahmasbi and Mahmoodi [6] studied the microstructure and mechanical properties of AA7022 aluminium produced by friction stir extrusion. They found that the samples produced with higher rotational speeds and lower forces had a far better surface quality and fewer surface cracks. Sharifzadeh et al. [7] evaluated the wear and corrosion resistance of magnesium alloy wire produced by friction stir extrusion. Their results show that the resulting microstructure reduces the coefficient of friction and increases the wear resistance compared to the raw material.

The microstructure of magnesium chips subjected to friction stir extrusion was modelled by Behnagh et al. [8]. Also, their mechanical tests showed that almost all recycled specimens can achieve higher tensile strength than the parent magnesium at room temperature. Baffari et al. [9] investigated the effect of friction stir extrusion process parameters on 2050 aluminium alloy. In this study, they investigated the effect of different heat treatment cycles on the mechanical properties and microstructure of this alloy. Two parameters were selected to test the samples using this process, which included rotational speed at three levels and extrusion force at four levels.

In the study of Li et al. [10], the flow of materials in the wire produced by friction stir extrusion method was investigated. They used AA2195 aluminium as a marker insert on AA6061 aluminium cylindrical billet to understand the material flow during the process. The results showed that the flow of material during the extrusion depends on the rotation rate and the extrusion force. Ansari et al. [11] studied the optimization of friction stir extrusion parameters by Taguchi method. In this study, process parameters including rotational speed, plunge feed rate, and extrusion hole size were optimized using the standard L8 orthogonal array. Microstructural studies showed that significant changes in the initial grains of magnesium ingots are caused by friction stir extrusion. According to the results of this study, high quality and flawless wires can be produced using the appropriate combination of production process parameters.

Tang and Reynolds [12] investigated the production of wire by friction extrusion using AA2050 and AA2195 aluminium alloy chips. The extruded wires were heat treated. Hot and cold cracks appeared in the produced wires depending on the rotational speed. In general, the increase of rotational speed increased the grain size in wires. Abu-Farha [13] studied the feasibility of fine-grained tube production by friction stir back extrusion process. AA6063-T52 aluminium alloy was used in that research. Recrystallization was observed in the tubes due to the frictional heat generated during the process. The results of this study showed that this process can produce sound tubes without any voids and internal cracks. Abu-Farha [14] studied the spiral friction stir extrusion of tubes made of AA6063-T52 aluminium alloy and AZ31B-F magnesium alloy. The rotational speed was 2000 rpm with a feed rate of 2.12 mm/s. Examination of the microstructure of the processed tube showed clear signs of fine-grained microstructure in the stirred region. The microstructural properties of pure copper tubes which were produced using friction stir back extrusion were investigated by Dinaharan et al. [15].

Their results showed that the friction stir back extrusion can produce a healthy copper tube. Sarkari and Movahedi [16] studied the microstructural evolution and mechanical properties of aluminium tube under friction stir back extrusion. The process was able to produce a tube with a fine-grained structure, which was due to the phenomenon of dynamic recrystallization in the stir zone. They observed that different areas were formed in the tube where different microstructural changes occurred.

The literature study shows that this method has already been used to produce wires and tubes using aluminium and magnesium alloys. In this paper, the feasibility of producing dissimilar double-layered wire has been studied using a modified friction stir extrusion process. This process is used to produce double-layered wire with aluminium coating on a steel core. The most important feature of double-layer wire is having different properties in one wire that can have various industrial applications. Production of bilayer wire by friction stir extrusion method reduces the costs, increases the production rate and efficiency due to the direct processing of chips into a product with a sound structure. Thus, the chief importance and novelties of the present work are as follows:

- Production of bilayer wire using a modified friction stir extrusion process.
- Covering a steel wire with a coating provided from aluminium chips.
- Applying the friction stir welding and extrusion processes simultaneously.

2 MATERIALS AND METHODS

The raw material in this process was aluminum chips created during the machining of aluminum rods without the use of coolant. "Fig. 1" shows the aluminum chips used in this study for the friction stir extrusion process. The aluminum alloy used was subjected to a quantometry test to determine its composition. "Table 1" shows the chemical composition of the alloy in terms of the weight percentage of the elements.

Table 1 Chemical composition of used aluminum alloy (wt%)

Al	Cu	Si	Fe	Mn	Mg	Zn	Cr	Pb
Base	3.56	1.01	0.56	0.31	1.14	0.30	0.01	0.23

Fig. 1 Aluminum chips used in the friction stir extrusion process.

In the friction stir extrusion process, a tool with high heat resistance is required due to the heat generated. For this reason, AISI H13 hot work tool steel is used to make the plunger and die. The hardness of the plunger and the die was increased to 55 RC by heat treatment. The stirring plunger has a central hole with a diameter of 5 mm to produce double-layered wire. It consists of two parts for easy exit of the wire. The schematic of the extrusion die is shown in "Fig. 2" . The specimens are 5 mm outside diameter and 70 mm long.

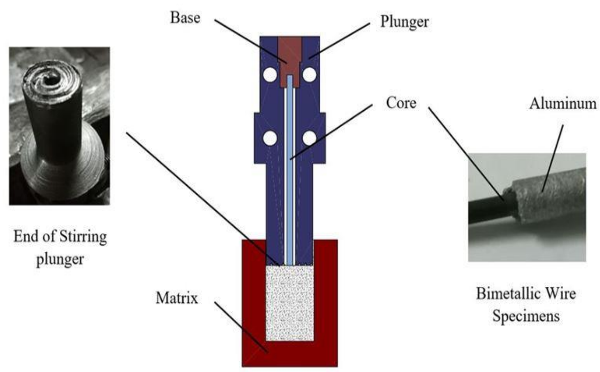

Fig. 2 Schematic of the modified friction stir extrusion process.

Figure 3 shows the forming steps. The friction stir extrusion of double-layered wire includes the following steps:

a) A suitable volume of aluminum chips is placed inside the die with a steel core for the production of double-layer aluminum/steel wire.

b) The initial penetration of the plunger together with the axial force causes the material to heat up.

c) As the plunger continues to advance, the material is plastically deformed and extruded in the reverse direction of the plunger.

d) In the last step, by advancing the plunger into the required depth, the wire formation is completed.

Rotational speed and feed rate are the most important parameters in the friction stir extrusion process. Mechanical properties, adhesion, material flow, strength, and microstructure are affected by these two factors.

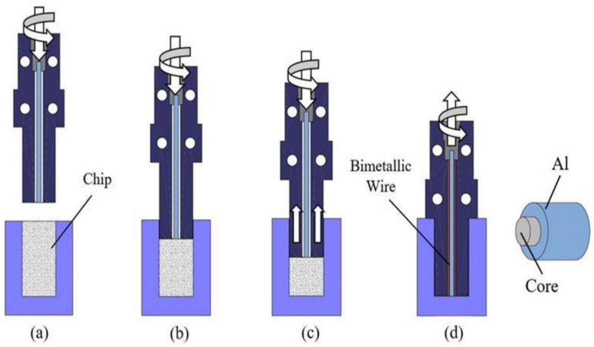

Fig. 3 Steps of modified friction stir extrusion to produce double-layered wires: (a): inserting the raw material inside the die, (b): initial penetration, (c): extrusion, and (d): wire formation.

To study the effects of rotational speed and feed rate in the experiments, each parameter was evaluated at two levels. These levels were selected based on several initial experiments. The studied factors and levels are given in "Table 2".

Table 2 The parameters and defined levels in the design of experiments

Factor	Level 1	Level 2
Rotational speed (rpm)	300	600
Feed rate (mm/min)	4	12

The tests are designed based on the full factorial design of experiments method. According to this method, all possible treatments are included.

After the friction stir extrusion process, the pull-out test was used to determine the adhesion strength of the aluminium coating. The non-destructive penetrant test was used to investigate the formation of cracks during the process. The Zwick/Z250 tensile test machine was used to perform the pull-out test. The pull-out speed was 1 mm/min. The schematic of the pull-out test is shown in "Fig. 4". After producing the extruded wires with the friction stir extrusion process, the samples are installed inside the holder. The core of the wire is mechanically passed through the retaining hole. Then, the core is removed from the cover by moving the clamp.

The liquid penetrant test is a non-destructive test that is an effective method for detecting surface defects, surface discontinuities, and pores that are not visible to the naked eye. Using this test, cracks with a width of more than 0.05 mm can be observed. The liquid penetrant test was performed according to the ASTM-E165 standard at room temperature. Figure 5 shows this test procedure.

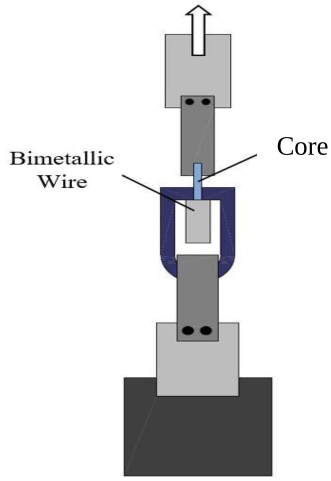

Fig. 4 Schematic of pull-out test.

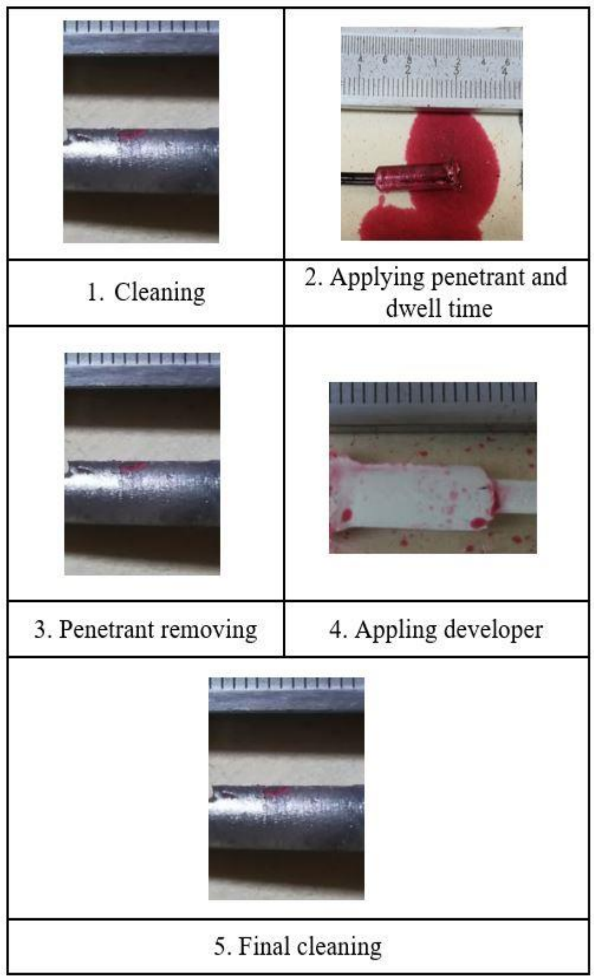

Fig. 5 Procedure of liquid penetrant test.

As shown in "Fig. 5", the surface was thoroughly cleaned to examine the samples. Moisture or any other contamination such as dust and oils prevents the penetrant liquid from penetrating. The penetrant is then applied to the surface. The dwell time for entering into cracks is 20 minutes. The surface is then cleaned with a clean cloth soaked in the cleaning fluid so that no trace of penetrant is observed on the surface. The developer is then sprayed on the surface to detect the defects clearly with the naked eye. The result is a change in color and the appearance of surface cracks. After surface evaluation, final cleaning should be performed due to severe corrosion of the penetrant.

3 RESULTS AND DISCUSSION

The results related to the adhesion strength of the specimens are shown in Table 3. Using the linear regression, the following equation was obtained to predict the adhesion strength of the double-layered wires produced within the range tested in this research.

$$N = 960 + 0.253R + 147F \quad (1)$$

Where, R is the rotational speed (rpm) and F feed rate (mm/min). The coefficient of determination (R^2) for this equation was 0.985 which shows that the model almost perfectly fits the data. According to "Fig. 6", specimens produced at a feed rate of 12 mm/min have much higher strength (approximately twice) compared to the specimens produced at a feed rate of 4 mm/min. Regarding the effect of rotational speed, two different effects were observed at high and low feed rates.

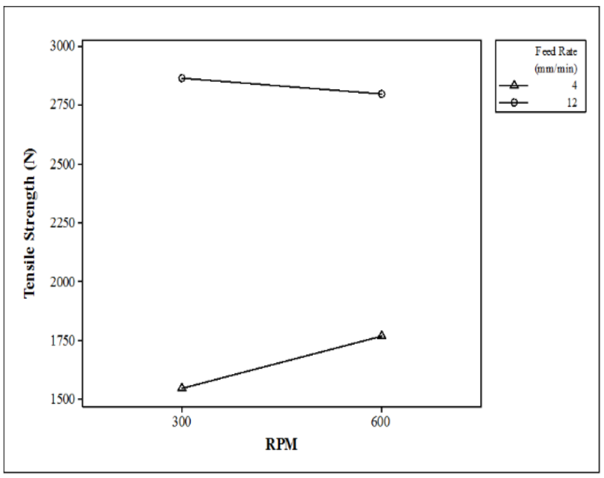

Fig. 6 Adhesion strengths of extruded parts.

At a feed rate of 4 mm/min, an increase in rotational speed leads to an increase in the adhesion strength, while an inverse trend was observed at a feed rate of 12 mm/min. Also, the slope of the increase in the low feed rate is slightly higher than the slope of the decrease in the high feed rate.

It is clear that changes in the feed rate have a more significant effect on adhesion strength than changes in rotational speed. This is also evident with respect to the coefficients obtained in the regression model ("Eq. (1)"). The coefficient of feed rate in this equation is 147, while the coefficient of rotational speed is only 0.235. This indicates the significant difference between the effects of feed rate and rotational speed on the adhesion strength within the range studied in this research.

It seems that at low feed rates, the material experiences more rotational motion, which leads to a decrease in strength. In other words, these results indicate that the connection occurs in the very first second. So, the increase in processing time, which is caused by a decrease in the feed rate, leads to the loss of the initial connections and reduces the strength of the connection (adhesion strength). The maximum strength obtained in this research was 2798.79 N, which was obtained from the extruded sample with the rotational speed of 600 rpm and the feed rate of 12 mm/min.

Table 3 Adhesion strength

Rotational speed (rpm)	Feed rate (mm/min)	Adhesion strength (N)
300	4	1550.42
300	12	2867.13
600	4	1770.75
600	12	2798.79

The penetrant fluid test was used to investigate the formation of surface cracks during the process. The images of the samples can be seen in "Fig. 7" after applying the developer. At a rotational speed of 300 rpm, the extruded wire with a feed rate of 12 mm/min has a long longitudinal crack. However, at a speed of 4 mm/min, many small cracks are observed all over the surface. It seems that by applying a higher feed rate that leads to an increase in the strain rate, the time required for the formation of an integrated coating is not provided to the material, which causes a large crack in the sample. At a rotational speed of 600 rpm, no cracks were observed at the feed rate of 12 mm/min.

However, several small cracks were created on the surface at the feed rate of 4 mm/min. It seems that at a rotational speed of 600 rpm, due to the higher rotational speed, more heat is generated during the process, which causes a better flow of material in the process and more adhesion of the coating to the core. It is concluded that the higher strain rate, which is imposed by higher feed rates, dissipates the small cracks.

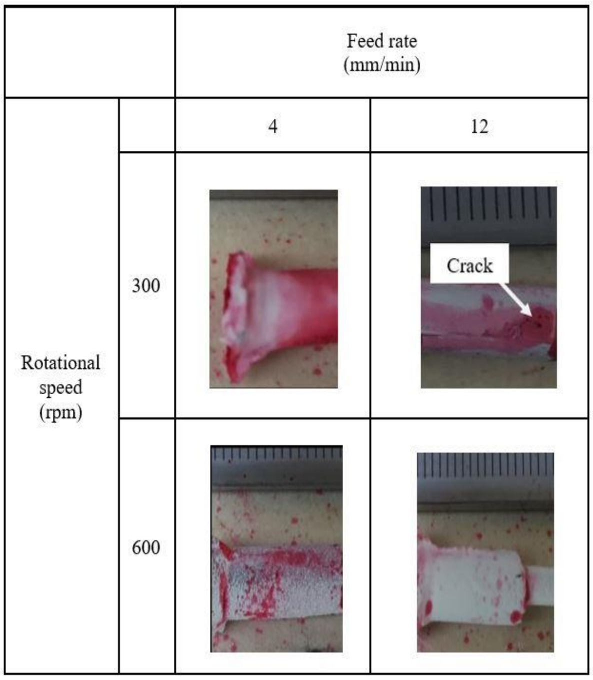

Fig. 7 Double-layered wires after using the developer in the liquid penetrant test.

4 CONCLUSION

The purpose of this study is to evaluate the feasibility of producing double-layered wire with heterogeneous alloys using the friction stir extrusion process. The parameters affecting this process, including rotational speed and feed rate are studied. The main results are as follows:

- Production of double-layer wire with heterogeneous aluminum and steel alloys is possible by using the proposed modified friction stir extrusion process.

- By choosing the correct process parameters, it is possible to produce double-layered wire with high adhesion strength and without surface defects.

- Increasing the feed rate increases the adhesion strength between the core and the coating.

- At low feed rates, with increasing the rotational speed, higher adhesion strength can be achieved. However, at high feed rates, the effect of rotational speed is reversed.

- The maximum adhesion strength and best surface quality (within the range of this research) is obtained at the feed rate of 12 mm/min and the rotational speed of 600 rpm, which is equal to 2798.79 N.

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