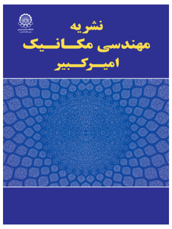

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Electroplastic friction stir spot welding for joining AA6061-T6 aluminum to galvanized DP590 steel

A. Barimani-Varandi, A. Jalali Aghchai*

Faculty of Mechanical Engineering, K. N. Toosi University of Technology, Tehran, Iran

ABSTRACT: The friction stir spot welding has shown great potential for joining low-ductility aluminum to high-strength steels. In the last decade, wide researches were done to achieve high strength and tool life enhancement in friction stir spot welding. The electroplastic effect, with its environmentally friendly nature and high efficiency, has resulted in a reduction of flow stress and tool wear, improvement of plasticity and material flow for various processes. On the other hand, adding nanoparticles to the friction stir spot welded area joint increased the tool wear despite the improved strength. In this paper, the joint strength and spindle output power are investigated in electroplastic friction stir spot welding process for joining of AA6061-T6 with 1 mm thickness to DP590 steel sheet of 1.5 mm. A 2^K design was used for statistical analysis considering four parameters of rotational velocity (1000, 2000 rpm), dwell time (2, 4s), electrical current (250, 500A), and adding SiC reinforcing nanoparticles. A quantitative study of the current density was performed by the finite element code with thermal-electric coupling. Results showed that electroplastic effect had a compatible impact with nanoparticles on strength improvement by accelerating the occurrence of dynamic recovery and recrystallization, and neutralized the negative effect of nanoparticles on tool life since created joints with failure loads above 7 kN.

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1- Introduction

Reducing the emissions as well as increasing the fuel efficiency request the wide use of lightweight aluminum alloys in the automotive industry. However, aluminum alloys are not completely replaceable with steels since the cost, performance, formability, and joining problems. So, the hybrid use of aluminum alloys and high strength steel alloys is an inevitable trend for fabricating lightweight assemblies made in aluminum to steel (Al/St) [1, 2]. To overcome the joining difficulties, in 2003, Friction Stir Spot Welding (FSSW) with the solid-state mechanism was first used in the Al/St assemblies for the rear door of the Mazda MX-5 [3].

In electrically-assisted processes, the effect of electrical current on the mechanical behavior of metal materials during the process is termed an electroplastic effect. This effect was firstly assessed and reported by Troitskii and Likhtman in 1963 [4]. The current density is applied to assess the amount of electric current passing through the cross-section. Significant changes will occur in the material behavior at the threshold current values of the current density [5]. Theories related to the electroplastic effect are divided into two groups of thermal and athermal effects [6]. Since most electroplastic manufacturing processes are performed at low temperatures, the athermal effect will be much more interesting.

According to the literature review, the reduction of the plunge force during creating the nanocomposite needs to be investigated for FSSW process. So, the athermal effect of the electroplasticity on the applied force on the tool, failure load and mode, and the addition of the nanoparticles in the FSSW process should be studied. In this paper, the ElectroPlastic Friction Stir Spot Welding (EPFSSW) process is investigated by adding SiC nanoparticles to join the AA6061-T6 to galvanized DP590 steel. The main purpose of this paper is to simultaneously achieve high strength joints and increase tool life with the help of EPFSSW process. For this purpose, a 2^K factorial design was used for the statistical analysis and modeling of the four process parameters. The finite element code was generated with a thermal-electrical coupling to assess the current density. In addition, the electroplastic effect on the failure force and load, microstructure, and output power of the spindle was experimentally investigated.

2- Methodology

In all experiment, the upper AA6061-T6 sheet with a thickness of 1 mm was FSSWed to the lower DP590 + Z140 steel with a sheet thickness of 1.5 mm. The tungsten carbide (WC) tool with 10% cobalt and hardness of 90 HRA was made by a simple cylindrical pin with a diameter of 4.6 mm and a shoulder diameter of 16 mm. To achieve a strong joint, the pin with a length of 1.6 mm with a penetration depth of 0.7 mm into the steel sheet was utilized. Also, to perform the process by applying nano powder, SiC nanoparticles with a diameter of 45-65 nm were used.

*Corresponding author's email: jalali@kntu.ac.ir

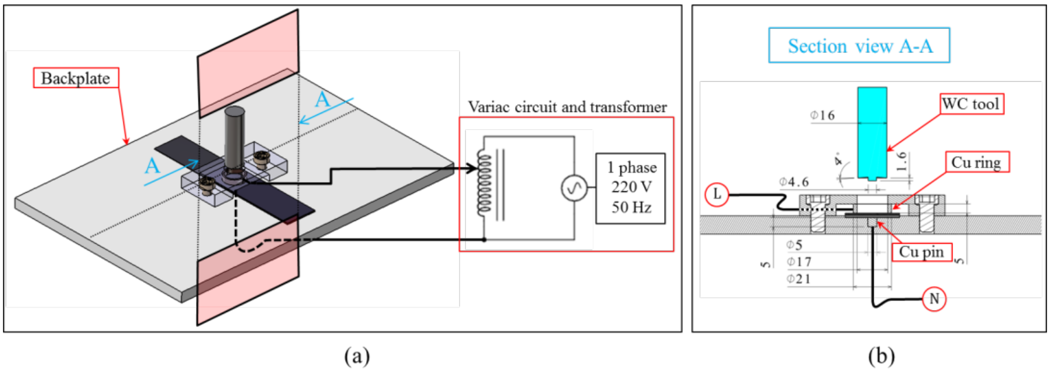

Fig. 1. (a) Schema of the electrically-assisted equipment and (b) longitude section with dimensions (mm)

The employment of alternating current 500 A started as the tool touched the aluminum sheet and was stopped after 10 s. The electrical current was manually adjustable by a variac connected to the transformer and a digital clamp meter. Fig. 1 schematically shows the electrically-assisted tools.

To quantify the current density generated by electrical current, the finite element code of ABAQUS/CAE 6.16 software with thermal-electric coupling and standard solver was utilized. The parts were discretized with the DC3D8E linear element with 8 nodes and degrees of freedom of temperature and electricity.

Planning the 2^K factorial design, statistical study and analysis of variance (ANOVA) considering three continuous parameters of rotational speed (A), dwell time (B), electrical current (C), and addition of SiC nano powder (D) as categorical factor, were performed using MINITAB 19 statistical software (Table 1).

It is noteworthy that in order to eliminate the effects of noise and reduce experimental errors, experiments were performed randomly with two replicates to extract the outputs of failure load and relative output power.

3- Results and Discussion

3- 1- Statistical analysis of DOE

Subsequent to assess the importance of all parameters, the model can be created by deleting insignificant terms. According to the ANOVA, the main parameters of dwell time, rotational speed, electrical current and SiC addition, respectively, had the greatest impact on the failure load. Additionally, the linear regression equation for the failure load is as follows:

Table 1. Limits of the parameters

Factors	Low (-1)	High (+1)
Rotational velocity (rpm)	1000	2000
Dwell time (s)	2	4
Electrical current (A)	0	500
SiC nanoparticles	No	Addition

$$F = -4468.3 + 927.2\,A + 1426.6\,B + 341.2\,C + 216\,D + 60.6\,A\times B - 19.1\,A\times C + 21.2\,A\times D + 118.9\,B\times C + 82.1\,B\times D - 25.4\,C\times D - 82.5\,A\times C\times D - 68.9\,B\times C\times D \quad (1)$$

In the study of output power effect, the main parameters of rotational speed, electrical current and powder had the most impact, respectively. The dwell time did not affect this output. The linear regression equation for the relative output power obtained from ANOVA is as follows:

$$P = 51.094 + 9.094\,A - 0.219\,B - 6.719\,C + 2.906\,D + 1.031\,A\times B - 0.844\,A\times C + 0.781\,A\times D - 0.031\,B\times C - 0.781\,B\times D + 1.219\,C\times D - 0.656\,A\times B\times D + 0.531\,B\times C\times D \quad (2)$$

3- 2- Distribution of current density

The distribution for the current density at the electrical current of 500 A is predicted in Fig. 2. Although the current density for the aluminum side is lower than that of the steel sheet; according to the theory of magnetoplasticity, the passage of electrical current can facilitate the movement of dislocations by creating a magnetic field, reducing flow stress, and thus improving material flow [7]. Besides, it is expected that the higher resistance of steel generates larger electroplastic effect. For the steel sheet, the maximum current density was about 45 A/mm2 at 500 A, which is higher than the threshold current density of DP590. As a result, the athermal effect of the electroplasticity promises useful merits includes that reducing the plunge force and increasing the strength obtained from grain refinement.

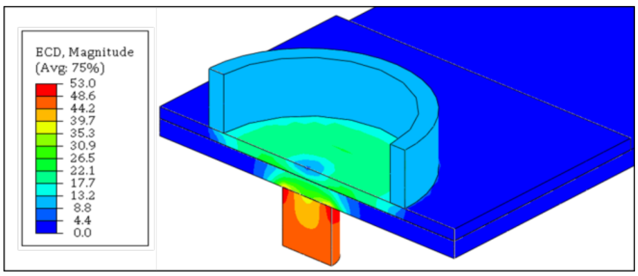

Fig. 2. Current density distribution at 500 A

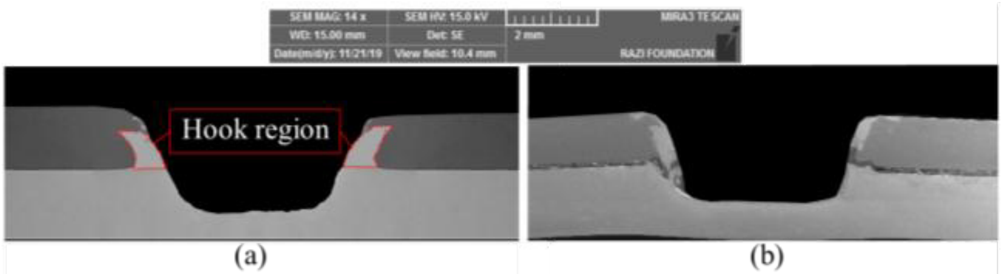

Fig. 3. Comparison of FE-SEM photograph of the joint cross-section for (a) I-SiC effects and (b) no effect.

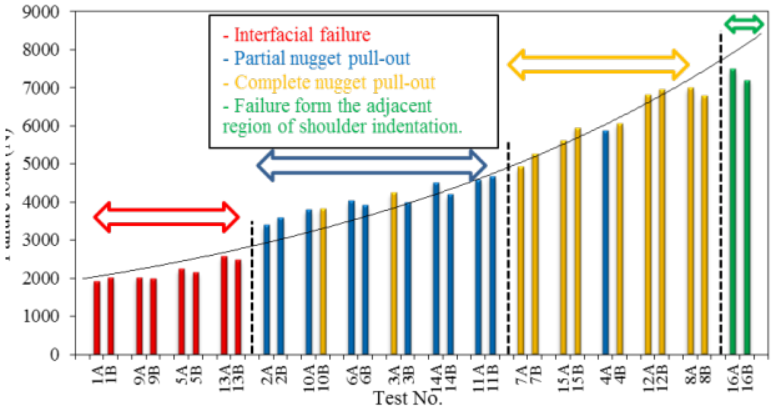

Fig. 4. Failure mode changes with increasing failure load

3- 3- Microstructure

According to the statistical results, adding the nanoparticles increased the average failure load and relative output power by 10 and 12%, respectively. The increase in the joint strength, as well as the force exerted on the tool, is due to the formation of the nanocomposite. Also, the experiments in the case of applying current density resulted in an increase of about 17% in the failure load and a 30% decrease in the relative output power, respectively. This dramatic reduction greatly affects tool wear and increases tool life. The athermal effect of electroplasticity increased the tool life with the occurrence of early recrystallization at low speeds; thus making it possible to achieve the desired strength. Furthermore, Figure 3 compares the simultaneous effect of electroplastic effect and nanoparticle addition (I-SiC) on the cross-section of the joint.

As is observed, in the case of simultaneous application of electrical current and nanoparticles, the improvement of plasticity and materials flow due to the electroplastic effect had led to the formation of a more continuous and complete hook area.

3- 4- Failure mode

Four failure modes were observed during the tensile shear testing of the FSSWed joints. Fig. 4 shows the failure load changes and modes. As depicted, the strongest joint of test number 16 failed with a fracture from the adjacent region of shoulder indentation. This experiment was performed at high levels of all parameters (Table 1).

This failure mode has never been reported in the FSSW of Al/St sheets [8, 9]. In this failure mechanism, the applied force overcomes the shear strength of aluminum in the region adjacent to the shoulder indentation; thus causes single-sided tensile failure. This mechanism confirms the creating of very strong joint by achievement of failure loads above 7 kN. In fact, in this experiment (No. 16), at a rotational speed and dwell time lower than other sources [10], suitable conditions in terms of grain size, diffusion and geometry of the hook area were created with the help of interaction effect of electroplasticity and nanoparticles addition.

4- Conclusions

The results showed that adding the SiC particles to the weld nugget can lead to the diffusion of the particles in the grain boundaries and the formation of the nanocomposite which reduced the tool life in addition to raising the failure load. The athermal effect of the electroplasticity accelerated the occurrence of recovery and recrystallization. Therefore, a fine-grained coaxial microstructure was observed in the stirring zone. Additionally, simultaneous application of electrical current and nanoparticles caused a significant increase of about 27% in the average failure load and a decrease of 13 % in the relative output power. As a result, it can be concluded that the electroplastic effect is complementary to the influence of the reinforcing nanoparticles which their positive effects are intensified on the joint strength. Besides, the strongest joints failed at the upper bound of the parameters with a failure load above 7 kN.

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