Çukurova Üniversitesi Mühendislik Fakültesi Dergisi, 38(4), ss. 993-1003, Aralık 2023
Cukurova University Journal of the Faculty of Engineering, 38(4), pp. 993-1003, December 2023

Aluminum Forming by Vaporizing Foil Actuator Welding

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Geliş tarihi: 28.07.2023 Kabul tarihi: 25.12.2023

Atıf şekli/ How to cite: ÖNDER, G.T., KÜLEKCİ, M.K., (2023). Aluminum Forming by Vaporizing Foil Actuator Welding. Cukurova University, Journal of the Faculty of Engineering, 38(4), 993-1003.

Abstract

Aluminum, has a wide range of uses, from industry to medical industrial products such as automotive, defense-aviation, and space. Aluminium has become a preferred material in applications where weight needs to be reduced. It is also used as a material in metal cladding and shaping applications. However, the high thermal conductivity coefficient of aluminum may cause some difficulties in the production process. These difficulties due to thermal conductivity may not allow to manufacture of desired products. In this study formability of aluminum with vaporizing foil actuator welding (VFAW) has been investigated as an alternative process to the traditional and solid state welding processes. By using different voltage values and separation distance parameters, the effects of these parameters on the formability of aluminum and copper sheet metal pairs with VFAW were examined experimentally. Experimental data show that voltage value is an important parameter in the VFAW process where a DC capacitor is used. In the VFAW process, where a 375 V voltage value is used, it has been determined that welding occurs in processes performed with three different separation distances (0.4 mm- 0.9 mm -1.5 mm). It was determined that 0.4 mm and 0.9 mm separation distances were effective in joining Al/Cu metal sheets with 0.1 mm thickness.

Keywords: Solid state welding, Vaporizing foil actuator welding, Aluminum, Sheet metal forming

Buharlaştırılmış Folyo Aktüatör Kaynağı ile Alüminyum Şekillendirme

Öz

Endüstrinin vazgeçilmez malzemelerinden olan alüminyum, otomotiv, savunma-havacılık ve uzay endüstrisinden medikal endüstriyel ürünlere kadar çok geniş bir kullanım alanına sahiptir. Özellikle parça ağırlığının azaltılması gereken uygulamalarda ihtiyaç duyulan bir malzeme konumuna gelmiştir. Ayrıca metal giydirme, şekillendirme uygulamalarında yapısal bileşen olarak da kullanılmaktadır. Ancak alüminyumun yüksek ısı iletim katsayısı, üretim sürecinde bazı zorluklara neden olabilmektedir. Geleneksel imalat teknikleri, özellikle bu termal sorun nedeniyle sağlıklı ürün elde etmekte zorluklar yaşanmasına sebep olmaktadır. Bu çalışmada, hem geleneksel hem de katı hal kaynak yöntemlerine alternatif olarak folyo buharlaştırma tekniği (VFAW) ile alüminyumun şekillendirilebilirliği incelenmiştir.

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Farklı gerilim değerleri ve durdurma mesafesi parametreleri kullanılarak, bu parametrelerin alüminyum ve bakır sac metal çiftinin VFAW ile şekillendirilebilirliği üzerine etkileri deneysel olarak incelenmiştir. Deneysel veriler DC kapasitörlerin kullanıldığı kaynak yönteminde, gerilim değerinin önemli bir parametre olduğunu göstermektedir. 375 V gerilim değerinin kullanıldığı VFAW prosesinde üç farklı ayırma mesafesi ile gerçekleştirilen işlemlerde (0.4 – 0.9 – 1.5 mm) kaynak oluşumunun gerçekleştiği tespit edilmiştir. 0.1 mm kalınlığa sahip Al/Cu sac metal levhaların birleştirilmesinde 0.4 mm ve 0.9 mm ayrılma mesafesinin etkili olduğu belirlenmiştir.

Anahtar Kelimeler: Katı hal kaynağı, Buharlaştırılmış folyo aktüatör kaynağı, Alüminyum, Sac metal şekillendirme

1. INTRODUCTION

In the USA, the Corporate Average Fuel Economy (CAFE) standards, which aim to improve the fuel economy of passenger cars and light goods vehicles (such as pickup trucks, minibuses, and panel vans), started to be implemented, in 1975. In this direction, significant incentives were provided for the use of lightweight materials [1,2]. In addition, an orientation was provided to the materials and manufacturing sector for the development of various products and technologies to increase fuel efficiency in different ways. Studies have come to the fore to ensure the balance of size, weight, and power in vehicles [3-9]. Aluminum and magnesium alloys, advanced high-strength steels (AHSS), fiber-reinforced polymer composites (including carbon and glass fibers), and advanced polymers (without fiber reinforcement) are currently the most effective material groups for reducing vehicle weight. For each material to enter the industrial market, there are important technical barriers such as performance, manufacturability, cost, and modeling [1].

Conventional cars are mostly made of steel, but their weight can be reduced by using materials that provide better strength-to-weight ratios such as aluminum or magnesium in a direct or combination construction [4,5]. Aluminum is among the most important non-ferrous materials and has a density of 2.69 g/cm^3, almost one-third of the density of steel (7.83 g/cm^3), making it possible to manufacture lightweight cars based on aluminum [5,9,10]. In addition, lightweight materials have an effective place in the manufacturing world, as they require very little energy and raw materials in their manufacture.

Sheet metal forming is among the important manufacturing technologies for large industry applications such as aerospace, and automotive [6]. Aluminum is one of the ideal materials for sheet metal forming. However, aluminum is very susceptible to melting problems, including the annealing stage, since it does not give a signal such as a color change before melting in heat shaping. Today, extrusion, rolling, and casting processes are used to shape aluminum, so aluminum is converted into various semi-products and products [7,8]. The extrusion process causes damage to both the material and the molds due to compression forces, and sometimes due to thermal reasons. The rolling process, technically, applies direct pressure to the material surface. During casting processes, air holes are formed due to material flow and porosity is the most common defect in parts cast from aluminum alloys. In addition, during the casting process, self-withdrawal, that is, size variations, occurs during solidification. With current manufacturing technologies, these production problems create difficulties in obtaining healthy products [11].

Vaporizing foil actuator welding (VFAW) is a pulse welding technology applied under similar conditions to explosion welding (EXW) and magnetic pulse welding (MPW) [4,12-14]. In VFAW, the drive mechanism is a wire or foil material. In this respect, it differs from other pulse welding methods driven by an explosive or electromagnetic coil [4,15,16]. Forming, cutting, powder compacting and welding applications have different application requirements. Basically, the actuator foil, target, flying metal materials, and a standoff plate separating these materials, are sandwiched between fixtures (Figure 1) [17,18]. VFAW, which is the same as EXW with this layout, gains superiority in that it does not require a chemical explosive and can be carried out in laboratory conditions.

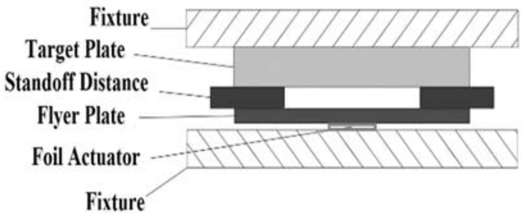

Figure 1. Vfaw general application scheme

Among the methods used today to join similar or different sheet metals, friction-based welding, impact welding, and roll bonding are the three solid-state welding methods [19]. VFAW technique is a rival technology to MPW [13].

This study aims to apply a new solid-state welding technique, VFAW [12], especially for forming and welding different metal sheets. For this purpose, it is aimed to create a mechanical locking between aluminum and copper with the experimental setup manufactured. In the study, four different voltages and three different standoff distance values were used through the VFAW process, and the formability of these parameters of aluminum sheet metal was evaluated with the results of sem analysis with the experiments carried out. In the literature, visual tests are commonly used to evaluate the joining process, and mechanical tests are used for strength [12,13,20,21].

2. MATERIAL AND METHOD

In this study, aluminum (Al) and copper (Cu), two different materials in terms of chemical and physical properties, were combined with a low-cost VFAW prototype manufactured by us. In this study, aluminum (Al) and copper (Cu), two different materials in terms of chemical and physical properties, were combined with a low-cost VFAW prototype manufactured by us. The experimental setup was created by the general application scheme [12] of VFAW technology. Unlike the literature, DC capacitors instead of AC capacitors are chosen to store energy. The aim here is to create an alternative to the classical application for the efficient use of energy.

For the experiments, an aluminum alloy (AA) sheet measuring 50 mm x 50 mm x 0.1 mm was used as a flyer, and a pure copper plate measuring 50 mm x 50 mm x 0.1 mm was used as a target (Table 1). The foil actuator is the most important element for this joining method. Actuator dimensions and design should serve to ensure joining. The actuator designed and used here is an aluminum foil of 0.1 mm thickness and has a 10 mm x 50 mm wide impact area. In Figure 2, the geometric shape of the foil actuator is depicted, while Table 2 provides the chemical properties of the aluminum material utilized as both the foil and the flyer. The wide sides (30 mm) in Figure 2, while providing the connection with the copper terminal, the narrowing middle section is called the active zone and geometrically helps the electrical discharge to occur in the area we want. The active zone is evaporated during the experiments.

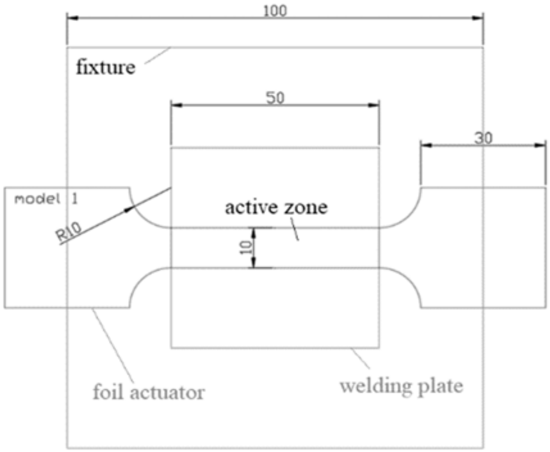

Figure 2. Actuator foil

In the manufactured VFAW process, the capacitor bank is built with direct current (DC) capacitors with a total capacitance of 10.000 μF, a short-circuit current rise time of 6.55 μs, an inductance of 20 nH, a resistance of 10 mΩ, 1.01 kJ max charging energy and 450 V max charging capacity (Table 3).

Table 1. Mechanical properties

Material name	Thickness mm	Elongation %	Yield strength MPa	Tensile strength MPa	Density g/cm^3
Aluminum	0.1	4.4	365	233	2800
Copper	0.1	5	250	295	89100

Table 2. AA chemical composition

Elements	Si	Fe	Cu	Mn	Mg	Cr	Ni	Zn	Ti	B
Contents (%)	0.238	1.082	0.0015	0.0066	0.0013	0.0018	0.0026	0.021	0.012	0.0016
Elements	Be	Bi	Ba	Cd	Ga	Na	V	Zr	As	Al
Contents (%)	0.00004	0.0026	0.00010	0,0007	0,010	0,0005	0,0088	0,0023	0,0087	98,59

For capacitors, the short-circuit current rise time is the time it takes for the current in the circuit to rise from zero to its first peak. A shorter current rise time means a higher current is reached sooner. Welding speed is an important privilege for welding technologies. The short-circuit current rise time (t) for a capacitor can be quickly estimated by the following Equation 1 [21]. Here R is the internal resistance of the circuit, L is the internal inductance and C is the capacitance.

$$t = \pi \left(2\sqrt{\frac{1}{LC} - \left(\frac{R}{2L}\right)^2}\right)^{-1} \quad (1)$$

The energy stored in the capacitors, and the maximum amount of energy, can be calculated with the formula Equation 2. Here E is the discharge energy, C is the capacitance, and V is the input voltage [22].

$$E = \frac{1}{2} CV^2 \quad (2)$$

After the actuator is insulated with insulating tape, it is fixed on both sides of the copper terminals in contact with the capacitors. Here, attention has been paid to the terminal-fixture-welding metals-actuator surfaces that should be conductive and insulating. Metals should not contact each other at unwanted points. Figure 3, shows how the fixture, copper terminals, and aluminum foil are placed. At the same time, the location of the weld metals can be seen in this figure. The aluminum foil is positioned under the flyer plate, which is the primary weld metal. Standoff distance is a gap that separates two weld metals and is formed with a PVC material. Two standoffs are used on the right and left of the foil. The target plate, which is the second weld metal, is placed on this standoff material. The stack created parallel to each other should be fixed between the fixtures.

The copper terminals are in connection with the capacitor bank at one end and the pneumatic switch at the other end. System components are presented in Figure 4. Pneumatic switch 1 is used to perform controlled discharge with remote control. Pneumatic switch 2 is used to ground the residual voltage value in the capacitors and thus protect both the system and the environment. The voltage values can be adjusted using a power unit. The alternating current is converted to direct current with the power unit, and charged to the capacitors via cables.

Table 3. Capacitor specifications

Capacitor	R	L	C	Nominal short circuit current rise time (µs)	Max charge voltage (kV)	Max charge energy (kJ)
	Impedance (Ω)	Internal inductance (H)	Capacitance (F)			
	0.01	0.00000002	0.010	6.55	0.045	1.0125

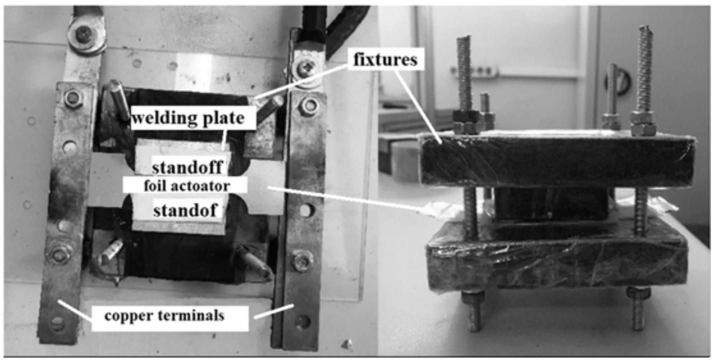

Figure 3. Fixture and actuator foil placement

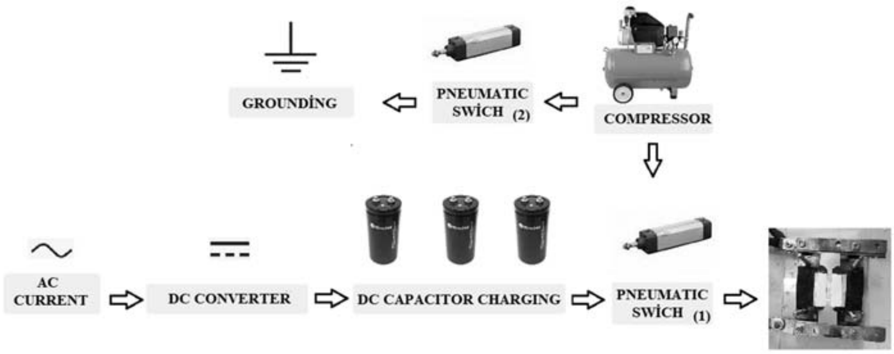

Figure 4. System components

In the experimental study, to examine the formability of the sheet metal with the VFAW method, some of the input values were kept constant in the experiments in which the "0.1 mm model 1 AA actuator foil" was evaporated. While keeping a constant 15 mm lateral distance, 6 kJ input energy, weld metals, and thicknesses, three different (0.4 -0.9-1.5 mm) standoff distances, four different (in the range of 350–425 V) voltage values were determined as variable (Table 4).

The lateral distance is the horizontal distance between two standoff materials (Figure 5). While creating this distance, it is ensured that it is larger than the width of the actuator foil, which is 10 mm.

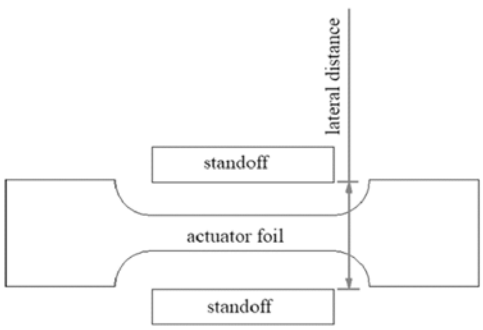

Figure 5. Lateral distance

Table 4. Experiment input parameters

Experiment	Actuator	Stand-off distance (mm)	Lateral distance (mm)	Flyer plate (mm)	Target plate (mm)	Input Voltage (Volt)	Input energy (kJ)
1.1	Model 1 0.1mm AA	0.4	15	AA 0.1	Cu 0.1	350	6
1.2						375	
1.3						400	
1.4						425	
2.1		0.9				350	
2.2						375	
2.3						400	
2.4						425	
3.1		1.5				350	
3.2						375	
3.3						400	
3.4						425	

3. RESULTS AND DISCUSSION

Traditional methods used when joining sheet metals, folding/tab-joint, pulling and pressing of a rivet, self-clinching, screw joint, and welding joints are countable [19]. With VFAW, a new joining technology, sheet metals can be shaped. This situation has been demonstrated in many studies in the literature for many materials and material combinations such as aluminum and its alloys, magnesium and its alloys, steel, and titanium [4,23-26]. In the present study, a combination of copper and aluminum has been created.

In VFAW, the heat generated during the process is very low, so thermal deformation does not occur in the joint area and therefore the metals. In this way, the base metal properties of the weld zone are preserved [27,31]. In addition, many studies are showing that the VFAW technique is a cost-effective and high-performance welding method [28-30]. In our study, what are the ideal joining conditions with VFAW for the Al/Cu material pair were investigated. System components for the designed VFAW prototype have been kept as simple and accessible as possible.

Table 5 is a list of outputs from the experiments. Here "input voltage" is the voltage value at which capacitors are charged, "residual voltage" is the voltage measured across capacitors after discharge has taken place. In the experiments, according to the same input voltage values, an average of 109 V for 0.4 mm standoff distance value, 161 V average for 0.9 mm standoff distance, quality connections are provided at 180 V values for 1.5 mm standoff distance. In addition, when all the test results were examined, it was seen that the voltage value between 100 V and 185 V was spent with DC capacitors with 6 kJ input energy to combine Al/Cu materials and it was sufficient for welding. In addition, in the data obtained, It was observed that the increase in voltage increased with increasing distance. The metals needed more voltage to make contact with each other as the distance increased. The values used at a distance of 1.5 mm are the highest voltage values.

In Figure 6, scanning electron microscopy (SEM) images of bonding surfaces for aluminum and copper weld metals obtained with VFAW are given. In this study, SEM images were imaged without sectioning. When the images are examined, It is observed that the so-called "mechanical locking" [14,32] welding occurs between the weld metals. However, to characterize the obtained bond strengths, cross-section images should be examined and searched for more regular couplings with different input energies. The materials to be joined for VFAW are in the first installation position, They are separated by a standoff distance between the flyer and the target plate to provide the necessary flyer acceleration [33]. In the study, when the images and input parameters are examined to determine the appropriate "standoff distance".

At 0.4 mm standoff distance, while creating an ideal welding image at 350 V-375 V-400 V values (Figure 6a,b,c), a connection was formed at 425 V values (Figure 6d), but melting was observed in places. Pulse welding processes do not require heating and melting events, melting and formation of brittle intermetallic compounds (IMC) can be largely avoided if appropriate welding parameters are provided [33,34]. IMCs e cause the weld metal to have poor mechanical properties (tensile, ductility, fracture toughness, fatigue strength, fracture) [37]. For this reason, welding methods that prevent the formation of IMC during welding are of great importance. The gas that expands as a result of the rapid evaporation of the foil creates a driving force for the flyer to be thrown toward the target [12]. The excessive kinetic energy of the flyer results in melting and continuous intermetallics at the weld interface [12,14]. This indicates that there is an upper limit for kinetic energy. Optimum conditions for welding should be investigated for each material separately. For this, there are studies in the literature that created a limit map called "weldability window" [14,35,36]. Welding can only take place when the parameters are in the appropriate welding range. The study was created in this direction.

Table 5. Experiment outputs

Experiment	Input voltage (Volt)	Residual voltage (Volt)	Used voltage (Volt)	Condition
1.1	350	250	100	Optimal
1.2	375	268	107	Optimal
1.3	400	280	120	Optimal
1.4	425	302	123	Irregular connection
2.1	350	240	110	No Welding
2.2	375	253	122	Optimal
1.3	400	222	178	Optimal
1.4	425	240	185	Optimal
3.1	350	183	167	No Welding
3.2	375	195	180	Optimal
3.3	400	210	190	Irregular connection
3.4	425	232	193	Irregular connection

At 0.9 mm standoff distance, 350 V sufficient and smooth coupling could not be formed (Figure 6f), the ideal connection was formed at 375 V-400 V-425 V values (Figure 6g,h,ı). 350 V and 0.9 mm could not provide jet formation together. Jet is one of the basic criteria required for the formation of the source [14,27,34,36], and rather than being a stand-alone criterion, it emerges when optimum conditions are met with other entry conditions. At a 1.5 mm standoff distance, the distance between 350 V and metals could not create sufficient bonding (Figure 6i), the ideal connection was provided at 375 V (Figure 6j), and the connection was formed at 400 V and 425 V voltage values (Figure 6k,m), but a regular surface shape and contact along the entire surface could not be achieved. Close contact is required for weld formation [27]. To achieve this close contact, the 1.5 mm distance contributed little to jet generation compared to the 0.4 and 0.9 mm separation distances.

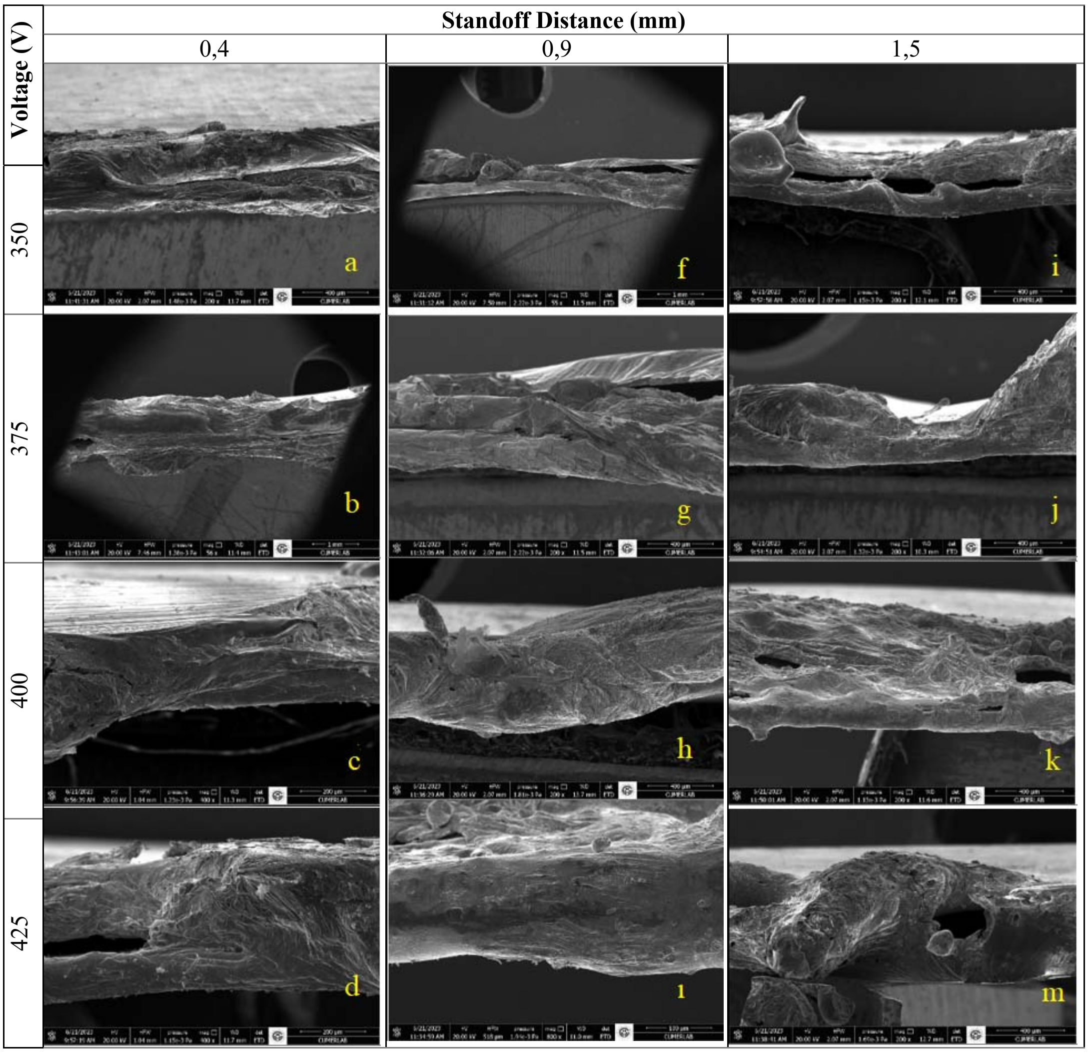

Figure 6. SEM micrograph showing pulsed welding of 0.1mm Al-0.1mm Cu weld sample by VFAW method at different voltages and standoff distances of VFAW

4. CONCLUSION

VFAW is a new and developing welding technology for the manufacturing world. Due to its structure, it has an important place because it is safer and easier to use compared to explosion welding, it has high performance especially when working with small and thin parts, there is no heat-affected welding zone and IMC formation is minimal.

In the study, VFAW has successfully resulted in the forming of aluminum and copper sheet metals. For this study, a welding prototype was created, using DC capacitors, unlike the literature, the ability of VFAW to combine thin metals with different properties such as Al/Cu was demonstrated. In metals, with the characterization of process parameters, VFAW technology will inevitably reach an important point in the manufacturing industry. The study is expected to be useful in situations where vehicle weight reduction is required and especially in applications where aluminum is required to combine with different metals. The success of this study serves as a guide for future studies on the VFAW shaping of several different metals and the characterization of process parameters.

In the method, 6 kJ input energy was created with 10.0000 µF / 450V / DC capacitors, three different (0.4-0.9-1.5 mm) standoff distances, and four different (350, 375, 400, 425 V) voltage values were used. The results obtained are as follows:

- Good microstructures and mechanical connections were obtained in VFAW formation utilizing the prototype manufactured using Al/Cu welding and DC capacitors.
- It has been shown that VFAW is affected by input parameters.
- When the effects of the voltage parameter on the formability of the sheet metal were examined, it was observed that the 375 V voltage value supported the weld formation at three different separation distances. It has been revealed that the voltage value is an important parameter in creating the most suitable welding conditions.
- When the effects of the standoff distance parameter on the formability of the sheet metal are examined, by staggering the standoff distance-tension value together, it has been observed that 0.4 mm and 0.9 mm standoff distance, together with a voltage value of 375-400 V, are efficient for joining Al/Cu metals with a wall thickness of 0.1 mm. The 1.5 mm standoff distance could not create enough jets for these metals.

4. ACKNOWLEDGEMENT

This study was supported within the scope of TÜBİTAK "1002-A Rapid Support Module" within the scope of the project numbered 222M455 and the project numbered INSTITU.21.001 of the Tarsus University Scientific Research Projects (BAP) Coordination Unit.

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