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Characterization of heating elements of different dimensions used in resistance welding of thermoplastic matrix composite materials

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ABSTRACT

Resistance welding is one of the most useful methods for joining of thermoplastic composite materials. In this method, the joining process between two thermoplastic composite materials by passing a current through a stainless-steel heating element under pressure for a certain period. Within the scope of this study, meshes with a width of 12.7, 25.4, 38.1, 50.8, 63.5, 76.2 mm and a length of 160 mm were used to characterize the joule heating performance. These meshes have a mesh range of 33, 45, 61, 91, 109 and 154 microns. The temperature values on the heating elements were observed with a thermal camera by giving different current values to the relevant elements. Results reveal that the 12.7 x 160 mm heating element with 33-micron mesh spacing reached 349 ℃ under 10 A current, and the temperature value increased with current. In addition, it was determined that the resistance values of the heating elements with different widths were determined by the relevant system and the resistance properties changed non-linearly with the width.

I. INTRODUCTION

A composite material is one that is created by mixing two or more components having dissimilar physical and chemical qualities to create a new material with enhanced properties over the components used alone. Utilizing their strengths, these elements, also referred to as the matrix and reinforcing elements, are joined to create a new material. While the reinforcing material contributes the required mechanical qualities, such as strength and stiffness, the matrix material surrounds the reinforcement material and gives it flexibility. Aerospace, construction, recreational goods, and healthcare devices are just a few of the industries that employ composite materials. High strength-to-weight ratio, longevity, resistance to corrosion, and wear resistance are only a few of their advantages. Metal matrix composites, polymer matrix composites, and ceramic matrix composites are typical forms of composite materials.

Polymer materials are classified based on their qualities, chemical structures, and production techniques. Polymers are categorized into natural and synthetic polymers, and they are further classified into thermoset, thermoplastic, and elastomers based on their heating behavior. Thermoplastic materials are polymers that can be melted and reformed repeatedly without enduring any chemical changes as a result of heat. Simultaneously, due to its simplicity of use in industrial studies as well as being an easily formed, light, durable, and cost-effective material,

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nowadays, its usage has grown popular, both in academic studies and in manufacturing operations, compared to other polymers.

Polyethylene (PE), polycarbonate (PC), polypropylene (PP), and polyamide (nylon, PA) are some of the most prevalent thermoplastics used today. In addition to these, the polyaryletherketone (PAEK) family and polyphenylene sulphide (PPS) are high-performance thermoplastic polymers. Injection molding, extrusion, and thermoforming are some of the processes used in order to treat thermoplastics. Composite material welding is used to combine two or more composite materials to build a bigger structure. It can be done in several ways, including adhesive bonding, fusion bonding, and mechanical bonding.

In addition to allowing complicated structures to be created in one piece depending on the manufacturing processes, composite materials necessitate joining procedures, which have drawbacks such as production mistakes, mold costs, and so on. However, thermoplastic matrix composites offer greater weldability than thermoset materials in polymer matrix composites due to their reversible features.

Assembling or joining thermoplastic composite structures is becoming more important to replace metallic or thermoset matrix composite materials in the aerospace, automotive, and marine industries to improve static and fatigue loads [1–2]. Many connecting procedures for unreinforced and reinforced thermoplastic polymers have been developed [3]. However, each approach has a narrow range of uses. Traditional connecting methods for thermoplastic composites are laborious and expensive. Boeing Corporation's Defense and Space Group conducted a cost comparison study and indicated that fusion bonding (welding) a composite wing structure vs. a bolted structure might result in labor savings more than 61% [4]. Thermoplastic adhesive bonding is challenging due to the difficulties of adhering adhesive compounds to thermoplastic polymers. Mechanical bonding methods have issues due to stress concentrations, galvanic corrosion, mismatch of the thermal expansion coefficient, and drilling damage to the reinforcing fibers. These issues can be greatly reduced using thermoplastic composite welding or fusion bonding [5].

Heat is generated by the contact resistance of the materials when a current is applied to the system in resistance welding. The heat generated is used to connect the materials. Thermoplastic composite materials have insulating qualities, and currents are supplied to the system via heating components. The heat required for bonding is provided by electrically resistive heating sources placed between material surfaces in this approach. There is no requirement for complex geometry molding for resistance welding [1-6]. When a current move through a heating element, heat is produced according to the Joule's Law. As shown below, the energy (E) emitted by the resistor is proportional to its resistance (R), current (I), and elapsed time (t).

$$E = I^2Rt \tag{1}$$

After the temperature losses on the materials are overcome, it increases towards the adhesion surfaces and after a while, it rises above the melting temperature of the thermoplastic materials and melts the material. The molten materials held under pressure adhere by pressure. After the materials adhere, the current flow is stopped, and it is expected to cool under pressure. After the materials have cooled, the pressure is released, and the thermoplastic composites are joined by the resistance welding [7].

Ageorges et al. [8] presented a comprehensive experimental investigation of resistance welding of carbon and glass fiber reinforced polyetherimide (PEI) sheets. Thermoplastic samples designed according to lap shear and double cantilever beam tests were resisted by using fabric and one-way heating elements. They characterized the statistical distribution of the resistance of the heating elements and evaluated the effects of temperature on the heating element resistance

Dube et al. [9] used carbon fiber reinforced polyetherketone ketone (CF/PEKK), carbon fiber reinforced polyetherimide (CF/PEI), and glass fiber reinforced PEI (GF/PEI) composite materials in their study to determine the effects of metal mesh heating element size on the resistance welding of thermoplastic composites. As heating elements, four different metal mesh sizes with mesh spacing of 0.152, 0.104, 0.089, and 0.043 mm were used. They discovered that the wire diameter and gap width had a significant impact on weld quality and performance.

Colak et al. [10] performed resistance welding process modelling for thermoplastic composites in their study. By developing heat transfer, degradation kinetics and consolidation models, they created the process window, which is defined as the applicable ranges of controllable process parameters. An optimization method called as Nelder-Mead was used to determine the process parameters. Thus, they have ensured that the welded joint results in the desired quality and with minimum processing time. They found the optimum process parameters and welding times corresponding to the process parameters for different thicknesses of APC-2 PEEK thermoplastic composites. It was determined that as the thickness of the APC-2 plates increased, the power requirement decreased, and the welding time shortened. They found that the thickness of the insulation material affects the welding time

Wei et al. [11] conducted an experimental study on resistance welding using three types of stainless steel (SS) mesh with different dimensions and electrical resistances as heating elements for welding carbon fiber reinforced polyetheretherketone (PEEK) composite composites. They conducted a study to determine the effect of metal mesh on welding process and performance at different power densities ranging from 29 to 82 kW/m^2. According to the given power densities, they observed the temperature value of the heating elements in which time.

Within the scope of this study, a series of experimental studies were carried out to determine the maximum temperature values that meshes with different properties can reach with the applied current, and to determine with which currents the operation temperature levels of thermoplastic materials to be used in joining processes can be reached.

II. EXPERIMENTAL METHOD / TEORETICAL METHOD

In this study, a resistance welding mechanism was designed as shown in Figure 1 in order to conduct experimental work. In the designed resistance welding mechanism, there is a plate that holds the copper plates and is controlled by pneumatic pistons for vertical movement. An insulating material, specifically Teflon, is placed between the plate and the copper plates. The power supplied by the power supply unit is delivered to the heating elements through the copper plates. There are pneumatic pistons that enable the movement of C10100 nickel-based copper alloys plates, which has electrical resistivity value 10 μΩ/cm, in the system. The meshes placed between the copper plates are then compressed and current is applied. In order for the system to work safely, necessary insulations are provided between the copper plates and the support parts. The temperatures generated by the current supply were measured by scanning the surface of the entire mesh with a Nikon thermal camera, and the maximum temperature data were determined separately for all type meshes with the relevant system.

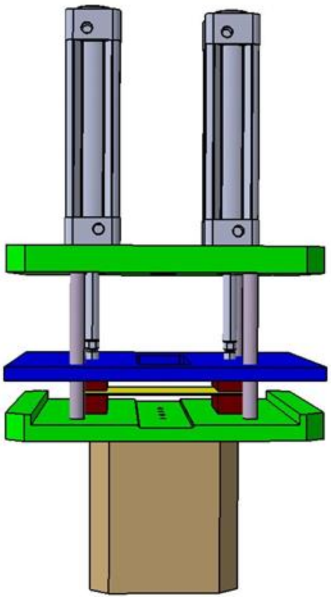

Figure 1. The designed resistance welding setup

The mesh spacing, mesh number, wire diameter, and opening area of the heating elements made of 316L stainless-steel material, which has electrical resistivity value 74 μΩ/cm, used in the study are shown in Table 1 and their 3D model images are shown in Figure 2. As known, 316L stainless steel material provides advantages in operation due to its austenitic characteristic.

In the study, the heating elements of different sizes in Table 1 were cut as 12.7 x 160 mm, 25.4 x 160 mm, 38.1 x 160 mm, 50.8 x 160 mm, 63.5 x 160 mm, 76.2 x 160 mm. The cut samples were powered by a DC programmable SORENSEN SGX50X200D-1DSAR model power supply. The temperatures formed on the heating elements were measured with the FLIR T530 thermal camera.

Table 1. Dimensions of heating elements

Mesh Spacing *(μ)*	**Mesh Number**	**Wire Diameter** *(mm)*	**Opening Area**
33	500	0.03	27%
45	300	0.04	28%
61	250	0.04	36%
91	180	0.05	42%
109	150	0.06	42%
154	100	0.1	37%

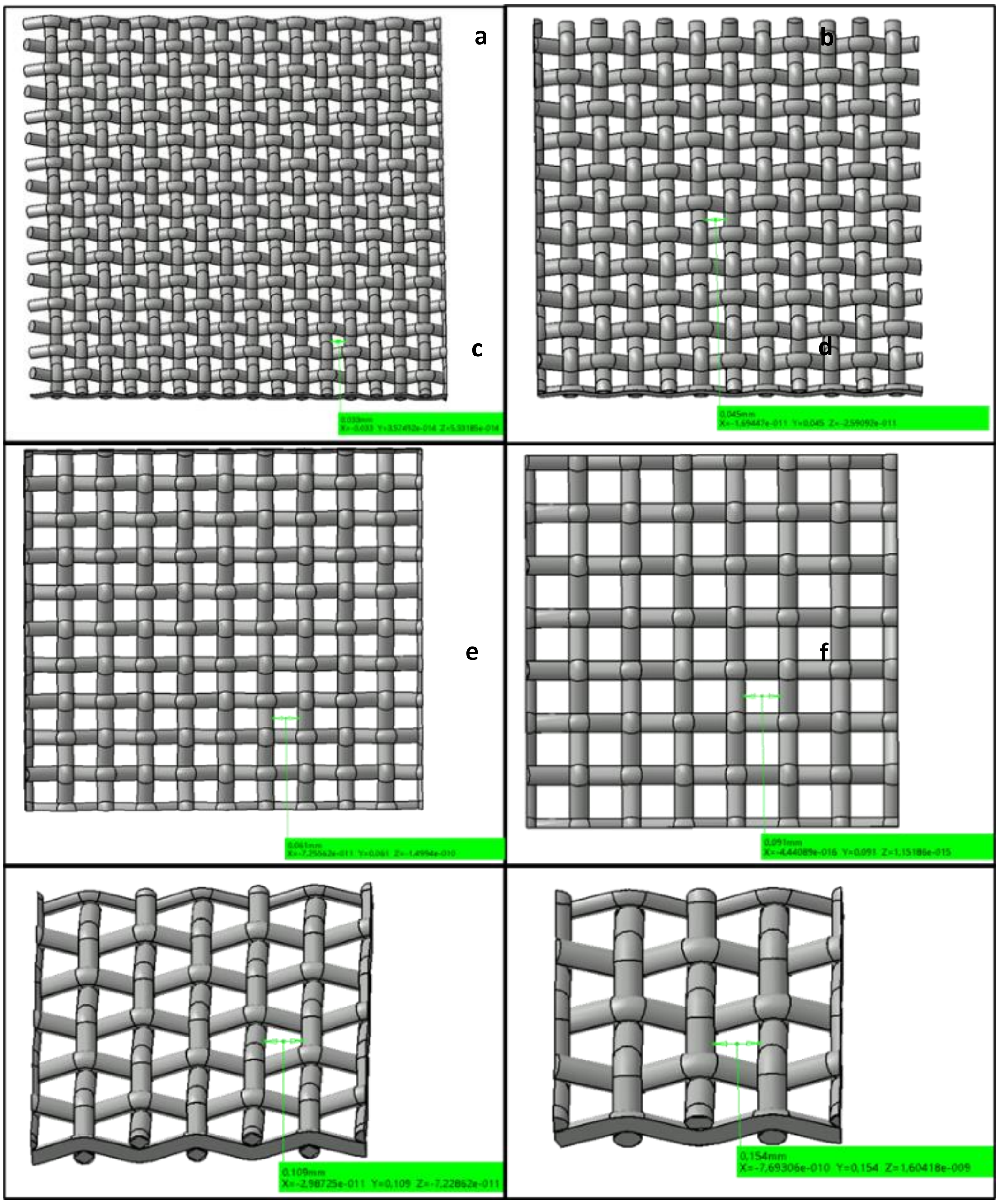

Figure 2. 3D model of heating elements with a length of 1x1 mm2 of heating elements with different mesh spacing a) 33 µm b) 45 µm c) 61 µm d) 91 µm e) 109 µm f) 154 µm

III. RESULTS AND DISCUSSIONS

The measured temperatures from 6 different heating elements according to different widths and different current values are shown in Figure 3. It was observed that more current is needed to reach high temperatures as the mesh gap increases. Considering the behavior of the heating element with 61-micron mesh spacing seen in Figure 3c, it is seen that the required current value to reach the desired temperature value is less than the heating element with 45-micron mesh spacing. The reason for this, was determined that the heating element with 61-micron mesh spacing and the heating element with 45-micron mesh spacing have the same thickness of wire diameter.

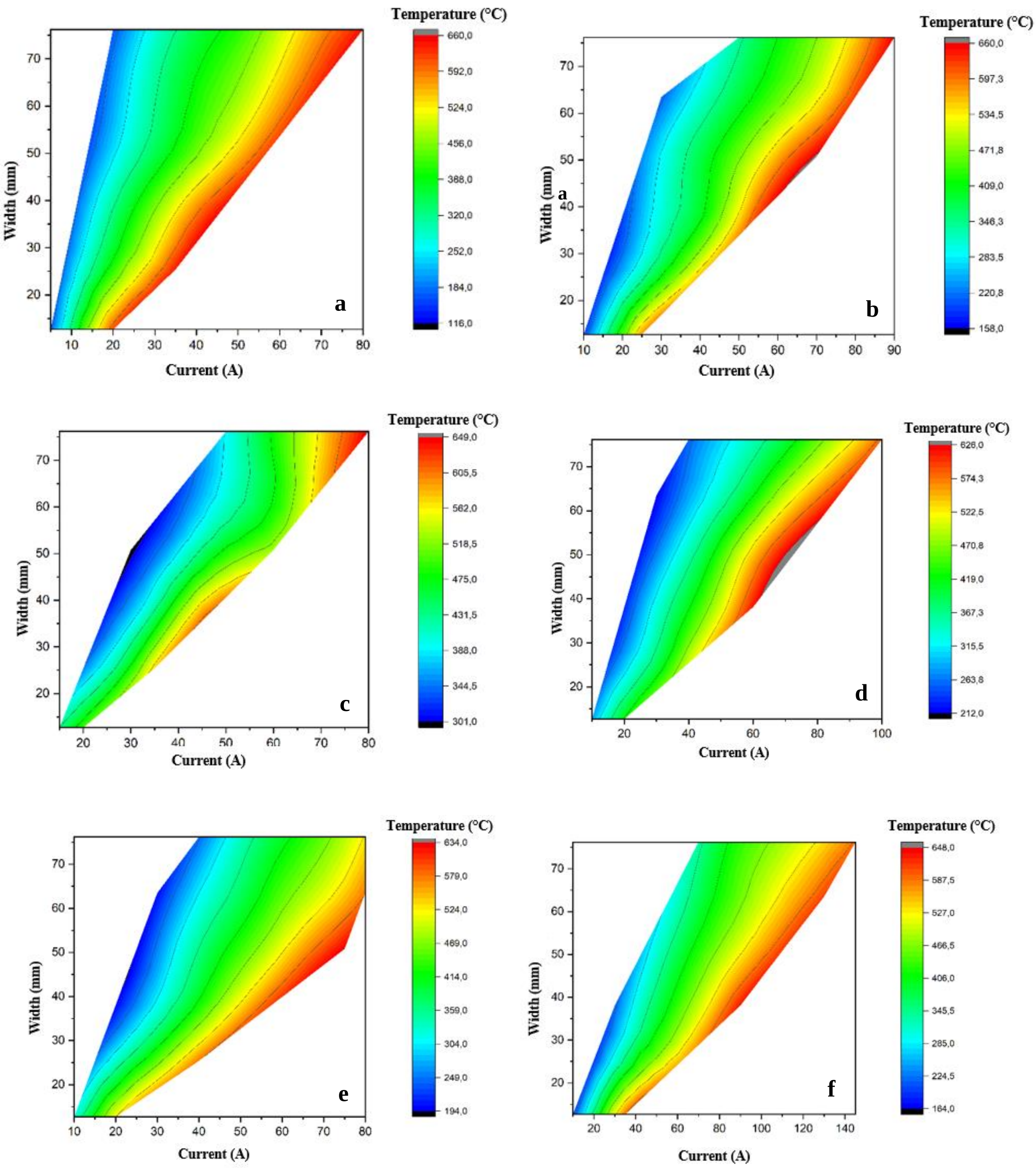

Figure 3. Current-width-temperature graph of the heating element with mesh spacing a) 33 µ, b) 45 µ c) 61 µ, d) 91 µ, e) 109 µ, f) 154 µ

In addition, it has been determined that as the width of the heating elements increases, the number of wires increases and the current per wire will decrease, and more temperature can be obtained by giving more current to the heating element. It has been observed that the current values given according to the width dimension do not increase linearly in order to reach the desired temperature value to be obtained from the heating elements.

The mathematical formulation for obtaining temperature values for each heating element was derived through regression analysis in the conducted study. The formulation, presented in Table 2, includes statistical metrics such as R-squared (R^2) and adjusted R-squared (R^2 adj) values.

Figure 4 shows the resistance values of the heating elements at different temperatures and currents. By reading the output voltage values of the heating elements, which are energized by the power source used, the resistance of the heating elements according to the varying temperatures and different widths, together with the given current values, was calculated from the connection between the current and voltage.

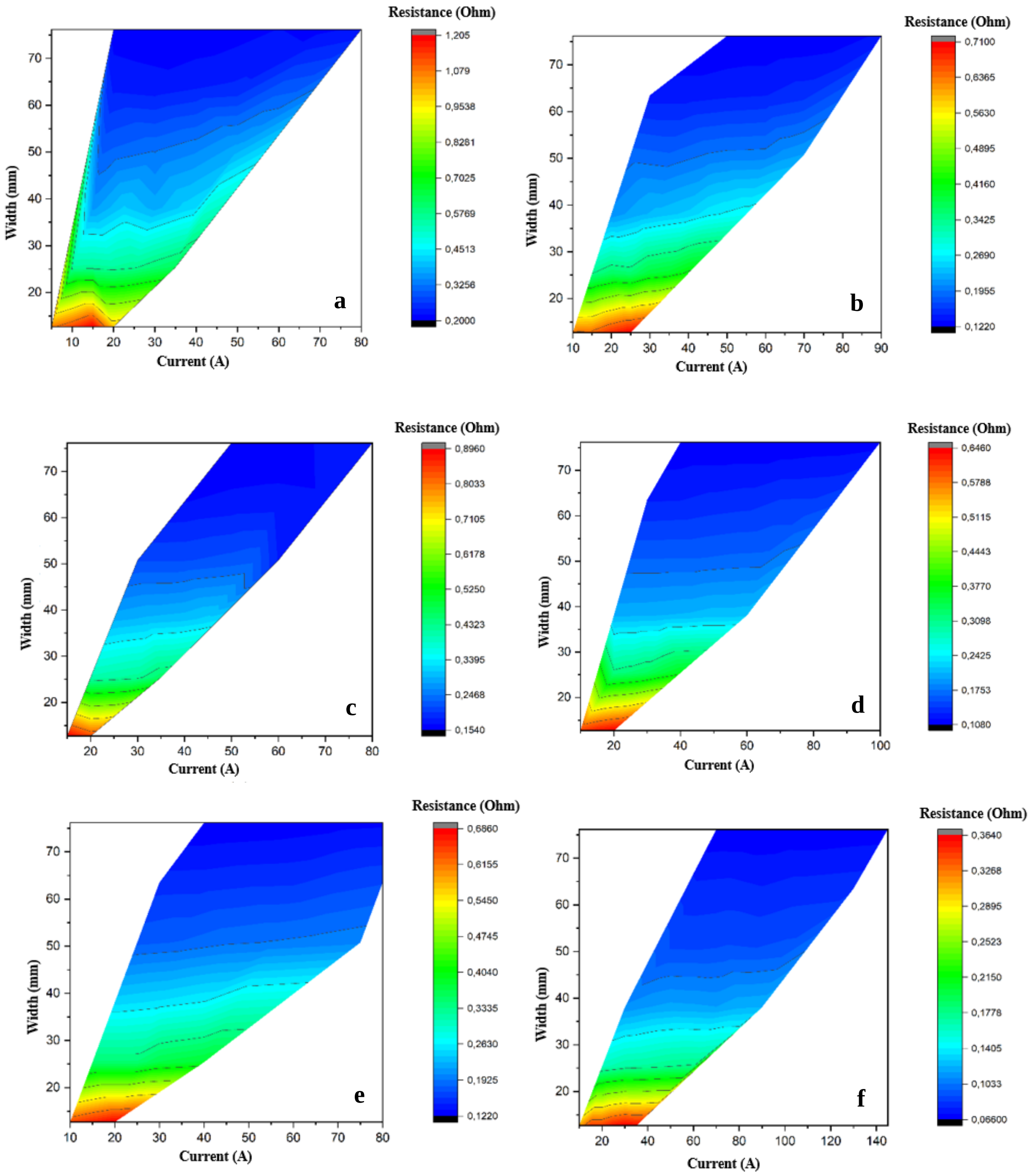

Figure 4. Current-width-resistance graph of the heating element with mesh spacing a) 33 µ, b) 45 µ c) 61 µ, d) 91 µ, e) 109 µ, f) 154 µ

The reason why the resistance value of the heating element with 61-micron mesh gap is higher than the heating element with 45-micron can be shown as the same wire diameter. It can be seen that this has a great effect since the resistance of the material depends on the cross-section area. In addition, since the heating elements produce energy according to the Joule law, the resistance values greatly affect the heating of the said elements.

Table 2. The formulas for temperature values of the heating elements based on current and width

Mesh Spacing *(μ)*	**Formulation**	R^2	R^2 **adj**
33	Temperature (°C) = 387,7 + 9,290 Current (A) - 5,849 Width (mm)	91.28 %	88.28 %
5	Temperature (°C) = 252,9 + 8,971 Current (A) - 5,047 Width (mm)	92.92 %	92.36 %
61	Temperature (°C) = 356,2 + 9,042 Current (A) - 6,113 Width (mm)	82.31 %	80.54 %
91	Temperature (°C) = 322,6 + 6,806 Current (A) - 5,013 Width (mm)	91.16 %	90.51 %
109	Temperature (°C) = 314,1 + 8,074 Current (A) - 5,553 Width (mm)	93.28 %	92.67 %
154	Temperature (°C) = 342,1 + 4,214 Current (A) - 4,259 Width (mm)	91.70 %	91.04 %

When we look at the study of Wei et al., [11], it was seen that the resistance value of the heating elements decreased as the mesh spacing of the these elements increased. In addition, it has been determined that the amount of current required to reach the desired temperature value increases with the increase in the width and thickness of the heating elements.

IV. CONCLUSIONS

In this study, a resistance welding unit was designed to weld thermoplastic matrix composite materials. By means of the designed resistance welding device, the temperature ranges that the heating elements made of stainless-steel material, which serves as an implant in the welding of composite materials, can be reached by cutting in 6 different sizes, the line length to which the current is supplied and in different widths, were measured. The measurement results show the minimum temperatures to be given to the composite material according to the melting and operating temperature of the thermoplastic composite materials to be welded. Due to the heat loss that may occur when composite materials are added on the materials, it has been determined that welding can be performed by taking 10% more of the current value in the current-width-temperature graph of the heating element desired to weld, in order to reach the operating temperature required for the welding of thermoplastic composite materials.

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