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METHODOLOGY TO DEVELOP OPTIMAL WELDING PROCESSES OF THERMOPLASTIC MATERIALS (EVA AND EVA / EVOH) USING THE HIGH FREQUENCY WELDING SYSTEM (HF)

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Abstract. The use of plastic materials has increased enormously in recent years. Currently there are lot of industrial and domestic companies that manufacture their products using the process of welding of thermoplastics with the high frequency welding (HF) technology. But when initializing their processes to manufacture products, they make the adjustments with the "trial and error" method until obtaining the optimal parameters with which the manufacturing equipment will be operated. This entail a series of expenses that impact the costs, quality of the product and damage to the environment due to the waste of discarded products. The production by means of processes of welding of thermoplastics using the system of high frequency (HF), is an integral part of the majority of the main processes of manufacture. The purpose of the methodology is to propose the development of optimal welding processes of thermoplastic materials (EVA and EVA / EVOH) using the high frequency welding system (HF), providing a benefit of reducing or eliminating the loss of time, resources, waste of materials, unnecessary expenses, obstacles and errors, reaching the goal of the process. The results of the answer show that the experiment # 27 the process has a Cpk of 2.98 and the experiment # 25 has a Cpk of 3.36, giving way to the methodology, where statistically allows to obtain a 6 Sigma process. In addition, the methodology allows to obtain the operational parameters of the thermoplastic welding process in control, reliable and predictable. It allows to have a process that can produce quality products to remain competitive in a growing global market.

Keywords: High frequency (HF), dipole, polarization, dielectric, thermoplastic welding.

METODOLOGÍA PARA DESARROLLAR PROCESOS ÓPTIMOS DE SOLDADURA DE MATERIALES TERMOPLÁSTICOS (EVA Y EVA/EVOH) USANDO EL SISTEMA DE SOLDADURAS DE ALTA FRECUENCIA (HF)

Resumen. El uso de materiales plásticos se ha incrementado enormemente en estos últimos años. Actualmente hay una gran cantidad de compañías industriales y domésticas que manufacturan sus productos usando el proceso de soldadura de termoplásticos con la tecnología de soldadura por alta frecuencia (HF). Pero al inicializar sus procesos para manufacturar productos, realizan los ajustes con el método de "prueba y error " hasta obtener los parámetros óptimos con los que se operarán los equipos de manufactura. Esto conlleva una serie de gastos que impactan el costo, calidad del producto y daño al medio ambiente por el desperdicio de productos descartados. La producción mediante procesos de soldadura de termoplásticos usando el sistema por alta frecuencia (HF), es parte integral de la mayoría de los principales procesos de manufactura. El propósito de la metodología es proponer el desarrollo de procesos óptimos de soldadura de materiales termoplásticos (EVA y EVA / EVOH) utilizando el sistema de soldadura de alta frecuencia (HF), aportando un beneficio de reducir o eliminar la pérdida de tiempo, recursos, desperdicios de materiales, gastos innecesarios, obstáculos y errores, llegando a la meta del proceso. Los resultados para la respuesta muestran que el experimento #27 el proceso tiene un Cpk de 2.98 y el experimento #25 tiene un Cpk de 3.36, dando paso a la metodología, donde estadísticamente permite obtener un proceso de 6 Sigma. En adición, la metodología permite obtener los parámetros operacionales del proceso de soldadura termoplástica en control, confiable y predecible. Permite tener un proceso que pueda producir productos de calidad para seguir siendo competitivos en un mercado global en crecimiento.

Palabras clave: Alta frecuencia (HF), dipolo, polarización, dieléctrico, soldadura termoplásticos.

Introduction

Plastic welding is a process for joining parts made of thermoplastic materials. Welding takes place by softening the areas to be joined. The polymer molecules acquire certain mobility by the action of an external agent (heat, vibration, friction, solvent). When both pieces are joined and pressure is applied, the molecules of both parts that need to be joined interact, interweaving. Once the action of the external agent is finished, the molecules' movement decreases, leaving an interlaced structure and forming the union of both plastic parts.

There are various welding processes for joining plastics on the market. Therefore, the ideal application of each of them depends on many factors.

Among the most common technologies in the industrial market for welding thermoplastic materials are:

- Hot plate welding.
- Heat-sealed.
- Laser welding.
- Ultrasonic welding.
- High frequency (HF) welding.

Thermoplastic welding using high-frequency technology is the process of melting and joining thermoplastic materials together using electromagnetic energy. Two electrodes create an oscillating electric field that begins to change as the polar molecules move within the materials, to orient themselves according to the electric field. The movement of these molecules releases energy in the form of heat and when enough energy is applied, the thermoplastic material begins to melt and bond with each other.

Currently, many industrial companies use this technique for different products: Medical Devices (IV drug container bags, blood bags, saline bags, oxygen bags, and bags for storing and maintaining sterile medical tools), automotive (plastic folders, heel pads or mats and seams for convertible covers and canvas covers), stationery (albums, book covers, diary covers, ID cards, folders, cardholders), consumer goods (umbrellas, raincoats, plastic bags, plastic covers, belts, gloves, guts, backpacks, and mixed fabric seals) and recreational goods (inflatable toys, balls, air cushions, inflatable ponds, waterbeds, product packaging), that manufacture their products using the thermoplastic welding process with high frequency (HF) welding technology.

Commonly, when initializing their processes to manufacture products, they make the adjustments with the method of "trial and error" until they obtain the optimal parameters with which the manufacturing equipment will operate (because they are subjected to factors like the type of material, "preheating" temperature, pressure, current, time of weld and the stage of weld cooling). Therefore, they can obtain a quality weld. This has an impact on the cost, quality of the product, and damage to the environment due to the waste of discarded products.

The article is structured into four topics and references, in addition to the summary and introduction and document structure. The methodology developed with optimal welding processes will allow the industrial sector to improve the quality of the final product and reduce costs associated with product waste.

In the first topic, we will address the definition of HF (high frequency) welding and the principle of plastic welding, to show a global vision of this technology.

The second topic is dedicated to thermoplastic materials, carrying out a summary of the principles, performances, and properties of these materials, to know how to interpret their performance. Besides, the theory of radio frequency (RF) welding is explained with its characteristics, and the operation of the HF welding generator is explained and identified.

The third topic will address the optimization where the use of the methodology is explained. An approach to identify, analyze, evaluate and design the experiment (DOE) that allows us to define the significant variables ("preheating" temperatures, pressure, current, welding time, and welding cooling time) is described as well. These are the parameters that affect the conditions in the welding process of thermoplastic materials using the welding system (HF), to optimize the results and thus be able to obtain statistical data independently.

Subsequently, different experimental design methods will be carried out to characterize some types of thermoplastic polymers that will be welded with the high-frequency technology. Besides, the results will be evaluated by their quality in the welding process.

The fourth topic is dedicated to results. The results obtained are discussed, highlighting the current limitations of the methodology. To evaluate the improvement of the thermal welding process with thermoplastic materials, the visual inspection methods with the magnification system and the welding resistance method will be used. Finally, the conclusion and contributions of this article are presented.

Method

What is HF welding?

The process of high-frequency welding (HF), also known as radiofrequency (RF) and dielectric welding, involves the fusion of material by supplying HF energy in the form of an electromagnetic field (27.12 MHz) that is normally applied between two metal electrodes, plates or molds. HF welding is accompanied by some pressure or force on the surfaces of the material that is going to be joined.

> Radiofrequency welding or (high-frequency welding) is the process of joining materials by using electromagnetic energy. Two electrodes create an oscillating electric field that begins to move and to shift the polar molecules within the materials, to orient themselves according to the electromagnetic field. The movement of these molecules releases energy in the form of heat. When enough energy is applied, the molecules begin to melt and bond with each other. Taken from (United Foam Plastics [UFP] Technologies, 2020)

Thermoplastic Materials

> They are materials that can be deformed thanks to heat and compression, maintaining their new shape when cooled. However, they can be softened by heat and re-molded, maintaining their physical and chemical properties when they return to their initial state of rigidity after cooling. Taken from (Wikiversidad, 2019).

Nevertheless, all thermoplastic materials cannot be welded using a high frequency, as they must have other specific characteristics, especially regarding their molecular structure (dipole), their dielectric constant, and their loss factor.

Electric dipole

> An electrical dipole is formed by two charges, one positive and one negative of the same value, separated by a certain distance. However, we can also define a dipole as a neutral system in which the center of the positive charges do not coincide with the center of the negative charges. A typical example is the water molecule. As oxygen is more electronegative than hydrogen, there is an accumulation of negative charge on the side where the oxygen is, and of positive charge on the opposite side. Taken from (Wiki, 2017).
>
> The unique structure of the polar water molecule, H2O, is the basis for the thermal response of water when subjected to an alternating field of RF energy. Taken from (Radio Frequency, 2019)

Water is polar due to the difference in electronegativity between the hydrogen and oxygen atoms. The highly electronegative oxygen atom attracts negatively charged electrons, making the areas around the oxygen more negative than the areas around the two hydrogen atoms. Therefore, the hydrogen side of the molecule is relatively positive to the negative side of the oxygen.

Podržaj and Čebular (2016, p. 1064) state the following:

> The molecules of the material used must have an electric dipole moment, which is defined as $p = \vec{I}Q$p" = " I →"Q" , where p is the electric dipole moment and $\vec{I}$I → is the displacement vector that points from the negative electric charge -Q

to the positive electric charge $+Q$. When this type of molecule is in an electric field (E), the torque (T) interacts with each other. The torque result is given by Equation 1:

$$T = p \cdot E \quad (1)$$

Chemical Structure

The polymer molecules that form a thermoplastic are linked together by intermolecular bonds, forming linear structures such as semi-crystalline or branched thermoplastics as amorphous thermoplastics. We could resemble its structure to a set of strings in which each one is a polymer. The strings may be intertwined, with greater force applied to separate each polymer molecule. Van der Waals' forces between the polymer molecules that form a thermoplastic material can be of different degrees depending on the chemical composition of the molecule itself and the spatial arrangement that it adopts. Depending on this, the adopted structure can be either amorphous or crystalline and both can exist in the same material. The amorphous structure is characterized by a disorderly dispersion of the polymer chains. Besides, it is responsible for the elastic properties of the plastics. The greater the number of amorphous structures is, the greater the elasticity of the thermoplastic, but it will have less resistance. In the crystalline structure, the polymer molecules are arranged in an orderly manner. Also, they are much more compact than in the amorphous structure. The intermolecular forces are stronger. Therefore, the crystalline structures confer mechanical resistance properties to the thermoplastic materials, making them resistant to loads, traction, and temperature. However, the greater the number of crystalline structures, the less elasticity there is and the more fragile it becomes. There are dozens of thermoplastics types and in each of them, the crystalline/amorphous organization and density vary. Nowadays, the most widely used thermoplastics are polyurethane, polypropylene, polycarbonate, and acrylics.

Amorphous and semi-crystalline thermoplastics performance

At room temperature, plastic is a hard material. Macromolecules are held together by intermolecular forces, and can barely move. If the temperature increases, the mobility of these macromolecules increases, as well as their elasticity and toughness. However, the strength of the material decreases. On the other hand, molecular orientation brings with it mechanical properties that affect the process. The mechanical characteristics of these materials can be illustrated with a rigidity versus temperature table, as shown in Figure 1. The vertical coordinate indicates the rigidity, and the horizontal coordinate indicates the temperature of the material.

The graph profile of amorphous materials will show that, at low temperatures, the material will remain in a solid-state. As the temperature increases, the material reaches a state called the vitreous state. This is characterized by the Glass Transition Temperature, (Tg). After this vitreous temperature Tg, the material will enter a transition zone known as the vitreous zone, where it will gradually lose its rigidity. When the glass transition temperature (Tg) is exceeded, the intermolecular forces become so small that when an external force acts, the macromolecules can slide over each other. Resistance drops considerably while lengthening increases sharply. In this temperature range, the plastic is in a thermo-elastic state, similar to the one of rubber. The vitreous zone can be seen in Figure 1. If the temperature continues to increase, a completely soft material will be obtained, similar to an elastic or rubbery melt that is not a liquid. Besides, the intermolecular forces are very small and tend to disappear. The plastic passes continuously from the thermo-elastic state to the molten state. This transition is characterized by the range of melting temperatures. In this case, we are not talking about a specific temperature. Figure 1 shows the vitreous zone Tg, the vitreous state zone, and the region corresponding to the soft zone.

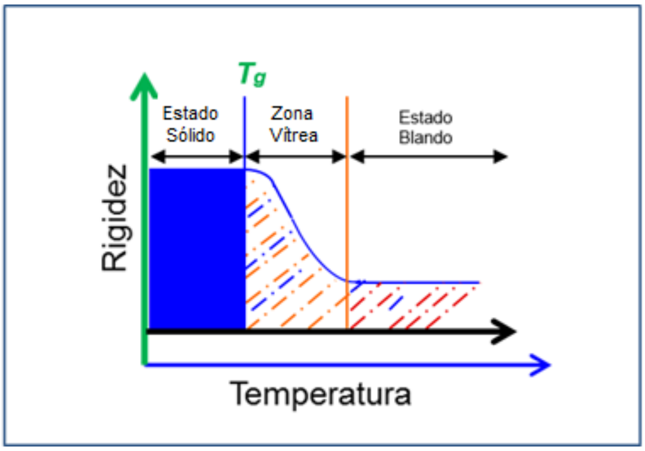


Figure 1. Profile of amorphous materials in the soft state zone.

Note: Source: Author's creation.

If the plastic heating continues, at some point, the chemical structure of the plastic gets decomposed. This limit is defined by the decomposition temperature (Tz).

> If the macromolecules have little branching, that is to say, few and short side chains, then it is possible that certain areas of the molecular chains are organized and arranged in a compact way next to each other. These highly ordered areas within the molecule are called crystalline regions. However, it should be taken into account that perfect or complete crystallization never occurs, as the chains' length prevents this from happening, even during polymerization when the chains start to intertwine with each other. Therefore, apart from the ordered regions, a part of the molecule always remains disordered, with regions distant from each other, called amorphous regions. Thermoplastics with both crystalline and amorphous regions are called semi-crystalline thermoplastics. Taken from (Wikiversidad, 2019).

Semi-crystalline thermoplastics are never transparent, not even when they are in their natural, uncolored form, but, because of the scattering of light on the border between the amorphous and crystalline regions of the plastic, they always look milky or cloudy. Figure 2 shows the performance of stiffness as a function of temperature for semi-crystalline materials. For this profile, it can be seen that, at a certain low temperature, the material is in a solid-state. This solid-state is represented in Figure 2 by the area marked with blue, in which the stiffness does not have important variations with the temperature. As with amorphous materials, at low temperatures, the material remains rigid and increasing temperature, it will reach the vitreous zone, just from the temperature called Tg, which is indicated in Figure 2. When talking about partially crystalline (semi-crystalline) materials, it is not common to use the term Tg. If the temperature continues to increase, beyond the vitreous zone, the material will lose some of its rigidity. In semi-crystalline materials, the vitreous zone is insignificant and corresponds to the amorphous part of the materials. Even so, it will remain in the solid-state. Figure 2 shows this vitreous zone.

If the temperature continues to increase, the melting temperature, $T_{m,}$ will be reached.

After T_m, a liquid material is obtained. This is why it is said that semi-crystalline materials melt and do not soften like the amorphous ones.

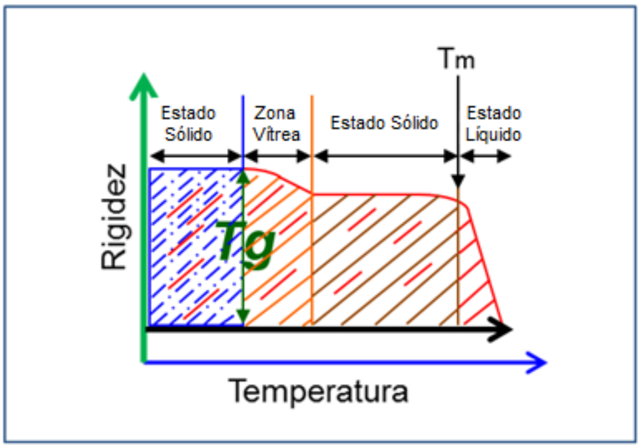


Figure 2. Profile of semi-crystalline materials in the liquid state

Note: Source: Author's creation.

Note that semi-crystalline materials do not have a large processing area like the amorphous ones, this makes it more difficult to melt. On the other hand, in the inverse process where the material is in the molten state and it is taken to the solid-state (decreasing the temperature), the process zone occurs faster than in the case of the amorphous materials. Figure 2 shows this performance.

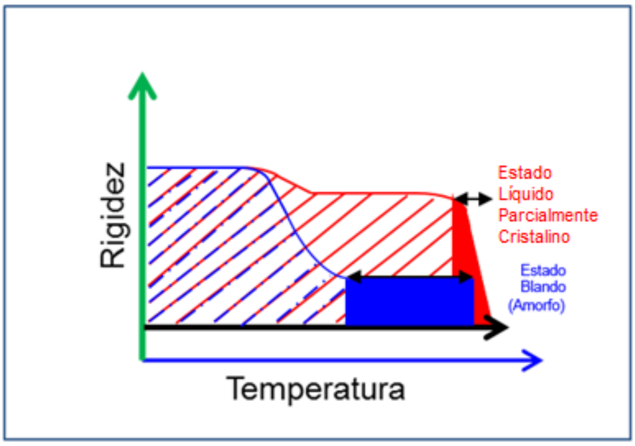


Figure 3. Graphic profile of semi-crystalline vs. amorphous materials.

Note: Source: Author's creation.

In Figure 3, it can be seen that the graph of rigidity vs. temperature shows a difference between amorphous and semi-crystalline polymers. The amorphous polymer clearly shows the three regions of visco-elastic performance: vitreous (visco-elastic), rubbery, and soft. Although there are differences in the timescale for the different polymers, the general shape of the curve is the same for all.

However, in semi-crystalline polymers, the phenomenon of the glass transition is covert in semi-crystalline thermoplastic materials, as these melt at temperatures higher than the glass transition of the amorphous zones.

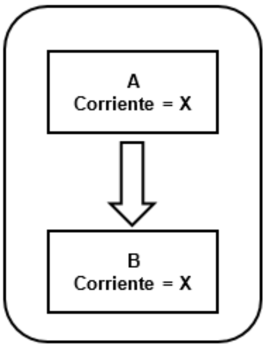
The semi-crystalline areas, made up of sections that extend into the amorphous areas, act as anchorage centers, making it difficult to soften the material and it performs as if it were reticular.

Electric heating.

Welding (HF) is based on this principle, which largely depends on the characteristics of the materials used.

The dielectric heating loss is a phenomenon of the materials that are subjected to an alternate high-frequency (HF) electric field. When the current passes through the material, it loses some of its energy, which is propagated in the material.

- If there is no material, the electric current passes through the field without losses: its intensity remains the same at the beginning (A) and at the end (B). (Figure 4).
- If a dielectric material is in the field (C), some electric current will dispel in it: its intensity will be stronger before crossing the material (A) and lower afterward (B). (Figure 5)



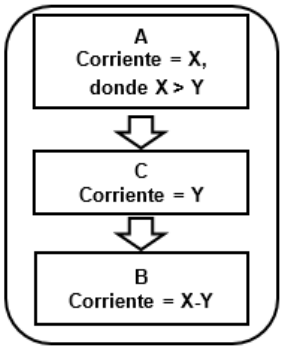


Figure 4. Without dielectric material. *Figure 5.* With dielectric material.

Note: Source: Author's creation

Naldini, Bianco, Amado, Nolasco and Perez (2016, pp. 2700-2701) state the following:

> In addition to this effect, there is also the heating produced by the dielectric losses due to conductivity, which develops within the RF current. At low frequencies, the power dispelled in the dielectric material is low due to the rapid alignment of the dipoles with the electric field, and the dielectric losses are negligible. As the frequency increases, the alignment of the dipoles becomes out of phase with the electric field, with a marked increase of dielectric losses. This results in a transformation of the field energy into heat.

During the process of dielectric losses, part of the energy is absorbed by the material and it is not returned. What happens then with that small part of the energy? According to the law of conservation of energy: "Energy is neither created nor destroyed, it is only transformed". And then, this energy has not disappeared, it has just been transformed into something other than electricity.

Dielectric constant

All materials have physical, chemical, or electrical characteristics, and one of them is the dielectric constant (ε). This material-specific dielectric constant is given for a specific frequency (for example, 10 MHz) and a precise temperature. Specifically, this dielectric constant indicates the ability of a material to be electrically charged. Besides, it is calculated regarding an insulating material base: water, whose ε = 1.

To calculate the constant, 3 steps are necessary:

Step 1: Calculate the voltage.

To transfer the energy, the material must be placed between two electrodes: one grounded and the other subjected to a high-frequency alternate voltage (HF). The voltage creates an electric field (E) between the two electrodes, expressed in V/m.

Using Voltage Equation 2, this electric field can be calculated,

$$E = V/d \qquad (1)$$

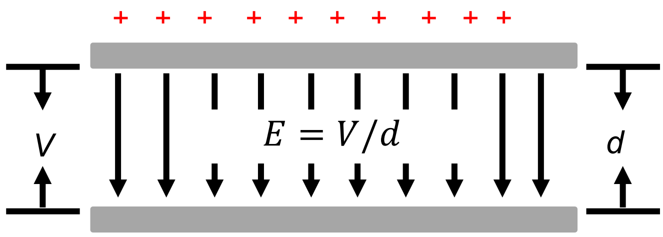


Figure 6. Dielectric constant in thermoplastic material.

Where,

- E = voltage
- V = electric field voltage
- d = *distance* between the electrodes

Step 2: Calculate the electric displacement

Electric induction (also called electric displacement field) is a field of the vector denoted by $\vec{D}\left(\vec{r} * \omega\right)$ as a function of spatial position and angular frequency. It is expressed in C/m².

Where,

- $\vec{D}$ = electric displacement
- $\vec{r}$ = function of the position in space
- ω = angular frequency or electromagnetic pulse

Step 3: Calculate the dielectric constant

Using the two calculations done, the expression $\varepsilon = D / E$, that is the dielectric constant of a material whose unit is in farads per meter (F/m), is deduced.

Where,

- ε = dielectric constant of the material
- D= electric displacement
- E= voltage

This constant allows us to choose the best material and the best welding parameters, but also, as it is the case of our devices, to calibrate a sensor device that controls the performance of the material and the welding.

As stated at the beginning, the dielectric constant depends on the frequency, but can also vary depending on factors such as humidity, temperature, structure, or composition of the material.

- Moisture, for example, influences the dielectric constant of a material, because water is a dipole. In fact, if water is present in an HF weld, the dipole molecules of the water will absorb the electrical energy.
- Temperature can also influence the dielectric performance of the material: the higher the temperature is, the greater the dielectric loss.
- The structure of the material is also a factor to consider, as it affects the performance of the dipoles. A material can have a crystalline or amorphous structure: as part of a solder (HF), the structure of the material must be amorphous.

The material composition is also important because the dielectric constant of a material, composed of several products, depends on the dielectric constants of the different products that form it. In general, the presence or addition of solvents or additives, polar or saline, increases the dielectric loss.

Optimization

To achieve the optimization of a thermoplastic welding process using high-frequency technology, a systematic methodology has been developed. This allows us to improve the welding process. The methodology of parameterization of the thermoplastic welding process using high frequency (HF) system helps to identify the initial parameters. Besides, it helps to eliminate the process of the traditional method of "trial and error", minimizing the process activities that do not add value (product rejecting - loss of production time being the least competitive product in the market) to create a faster and more efficient process. This leads to a transformation of the product or service in a functional way. But at the same time, it is good for the first time, and, at the end of the process, satisfies the client and makes the process to be cost-effective.

During the process of thermoplastic welding using high frequency, several variables involve the production of the final product, which may have different qualities in the finished products. Through experience, the traditional method of "trial and error" has been used to find the appropriate values for the variables involved. Therefore, it is necessary to determine the convergence of the variables that define the production process, which is better known as process optimization.

The research aims to replace the traditional "trial and error" method with a more engineering and formal way to identify the problems and successes of each decision-making during optimization, starting using new molds and changing the material to use the same mold.

To optimize the thermoplastic welding process using high frequency (HF) system, it is recommended to use the parameterization flowchart of this process system. See Figure 4-7.

As a starting point, it is necessary to have the specifications of the product that is going to be welded. In this phase, the functionality and purpose of the final product are defined and explained, and the corresponding information is obtained to verify or confirm the compatibility with the high-frequency technology.

The second phase continues with the identification of the characteristics, dielectric, mechanical and thermal, of the thermoplastic material to be welded. The purpose is to know its performance and compatibility with radio frequency technology and molds definition (electrodes) and mathematical calculations according to their applications, leading to the verification of the design already completed or the electrodes' new design to be made. At the same time, the specifications of the thermoplastic provided by the manufacturer are verified.

In the third phase, the specifications of the machine provided by the manufacturer are developed for the identification and specification of the mold press, type and specifications of the molds (electrodes), HF generators, and material voltage systems. The purpose is to understand the ranges of operational parameters available to be used in the experiments (DOE), for the identification of the process critical variables.

For the fourth phase, we continue with the compatibility checks of the machine vs. the product to be welded, to verify if the machine can weld the product meeting the required product specifications.

In the fifth phase, we carry on with the characterizations of the thermal, mechanical, and electrical main stations of the machine, which in turn are related to the significant variables (HF voltage, pressure, and welding time) of a thermoplastic welding process using high-frequency technology.

For the sixth phase, we continue with the development of the design of experiments (DOE) to search for the optimal parameters of the significant variables (Percentage of the Variable Capacitor-HF Voltage, Applied Pressure (Force), Welding Time, Temperature of the Mold Cooler).

In the seventh phase, the design results of experiments (DOE) are evaluated and the optimal parameters of the significant variables are determined. The suggested parameters are then confirmed, and the process is analyzed statistically. The repeatability and consistency of the process will be evaluated with a statistical program.

In the research work, we use the MiniTab program to evaluate the process capability "Process Capability".

As a starting point, the dielectric and mechanical characteristics of thermoplastic materials for the welding process were determined. Afterward, we continued with the development and analysis of the high-frequency technology and preliminary procedures of the area to be welded. This allowed us to identify the problems that may arise at the time or after the welding process.

Then, the characterization of the thermoplastic welding process was presented. This allowed the determination of the process of significant variables. This leads as well to the development of the experiment designs that allowed to optimize the significant variables of the thermoplastic welding process.

For the parameters 150 Kg, 200 Kg, 300 Kg, and 450 Kg of press 1, where we had an average of a Cpk = 4.76, equivalent to a 6 Sigma process, where statistically it allows us to observe that the process is controllable, reliable and predictable.

- The parameter 150 Kg, had a Cp 5.22 with a Cpk 3.69, for a 6 Sigma. (See Figure 7).
- The parameter 200 Kg, had a Cp 7.83 with a Cpk 5.90, for a 6 Sigma. (See Figure 8).
- The parameter 300 Kg, had a Cp 5.22 with a Cpk 4.63, for a 6 Sigma. (See Figure 9).
- The parameter 450 Kg, had a Cp 5.87 with a Cpk 4.82, for a 6 Sigma. (See Figure 10)

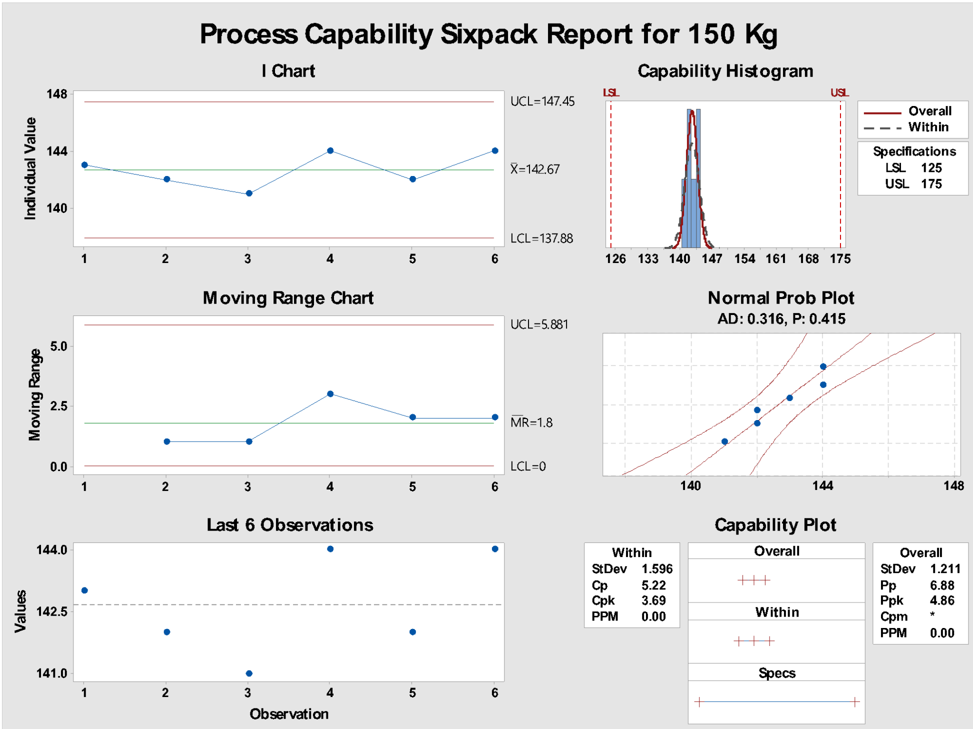


Figure 7. Process capacity of press 1 at a force of 150Kg

Note: Source: Author's creation.

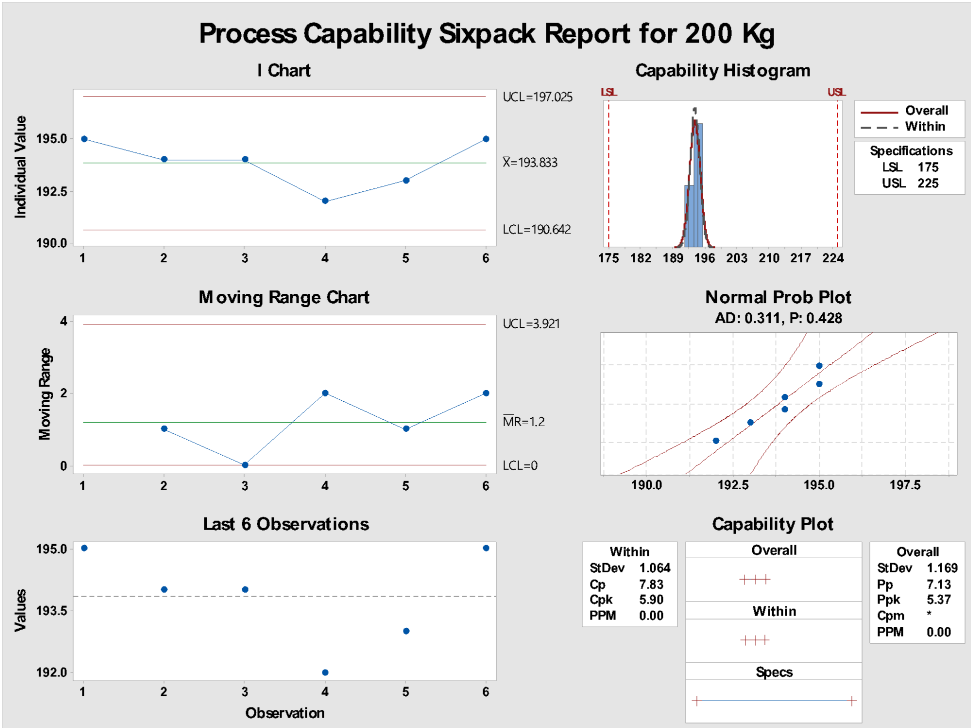


Figure 8. Process capacity of press 1 at a force of 200Kg

Note: Source: Author's creation.

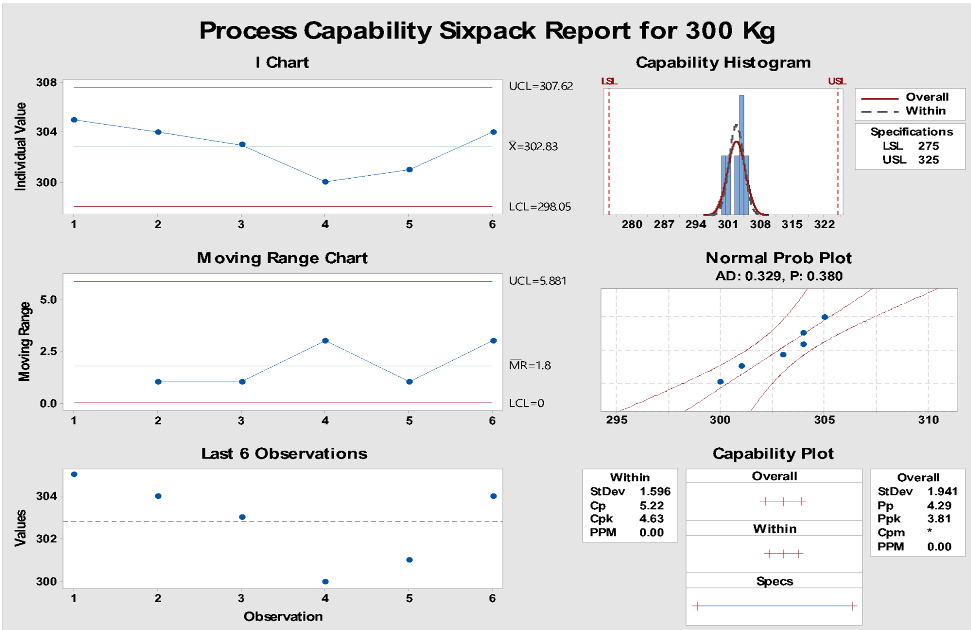


Figure 9. Process capacity of press 1 at a force of 300Kg

Note: Source: Author's creation.

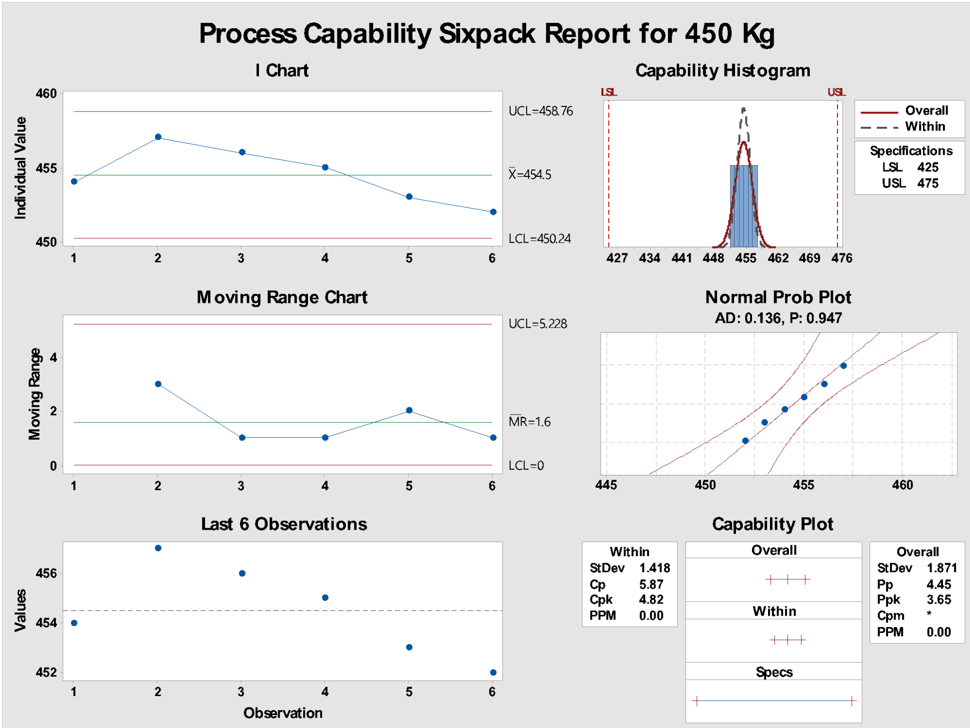


Figure 10. Process capacity of press 1 at a force of 450Kg

Note: Source: Author's creation.

For the parameters 850 Kg, 1050 Kg, 1750 Kg, and 1900 Kg of the press 2, where we had an average of a Cpk 3.66, equivalent to a 6 Sigma process.

- The parameter 850 Kg, had a Cp 17.67 with a Cpk 7.75, for a 6 Sigma.
- The parameter 1050 Kg, had a Cp 4.70 with a Cpk 1.88, for a 5.5 Sigma.
- The parameter 1750 Kg, had a Cp 4.70 with a Cpk 3.16, for a 6 Sigma.
- The parameter 1900 Kg, had a Cp 3.92 with a Cpk 1.83, for a 5.5 Sigma.

Based on the results of the presses' characterization, we can conclude that the performance of presses 1 and 2 are of high efficiency because both had similar process windows. This leads to a qualification window with the same tolerance for both, since the tolerance of the force parameters is approximately 8 times higher than the result obtained in the qualification window of each of the presses. This gives a result of a Cpk of 1.67, which is equivalent to a 5 Sigma process, obtaining a process higher than the industry standard, where the Cpk is 1.33.

After completing the experiment designs (three factors with three variables), the variables selected were: Percent of Variable Capacitor, Welding Time, and Mold Cooler Temperature (electrodes). These variables were analyzed with the MiniTab program using the main effects graph, where the main effects graph analysis is defined by examining the differences between the level means for one or more factors because there is a primary effect when different levels of a factor affect the response differently.

In Figure 11, the graph illustrates the main effects of the different variables: (Percent of Variable Capacitor, Welding Time, and Temperature (°C) of the Mold Cooler), showing how they affect the response (weld thickness) differently.

Analyzing the variables versus the product specification, where the weld thickness values must be between 0.35 millimeters and 0.45 millimeters, it should be observed that when the line is not horizontal (not parallel to the X-axis), then there is a primary effect. Different factor levels affect the response differently. The steeper the slope of the line is, the greater the magnitude of the main effect (thickness of the weld).

Obtaining the results, the variable that most affects the thickness of the weld is the Welding Time because its slope is more aggressive (because the line is not parallel to the X-axis). This response confirms the result that was observed in the experiments, where there was stated that the longer the welding time is, the thickness of the weld approached the lower limit of the specification and if the time continued to increase, there was sometimes a "flash" in the weld (Figure 12). Figure 11 also illustrates that the second factor that affects is the Cooling Temperature of the molds (electrodes), concluding that at higher temperatures (°C), the cooling time increases the weld melting, as the material becomes softer before the weld is applied. Finally, there is the percentage of the Variable Capacitor, since its result is almost linear to the response of the weld thickness. This is because the capacitor responds to the resistance of the material, but while the thermoplastic material is changing its solid state to a soft state. The effect of the thermoplastic material becomes more conductive, because of this effect, the capacitor tends to control its power faster.

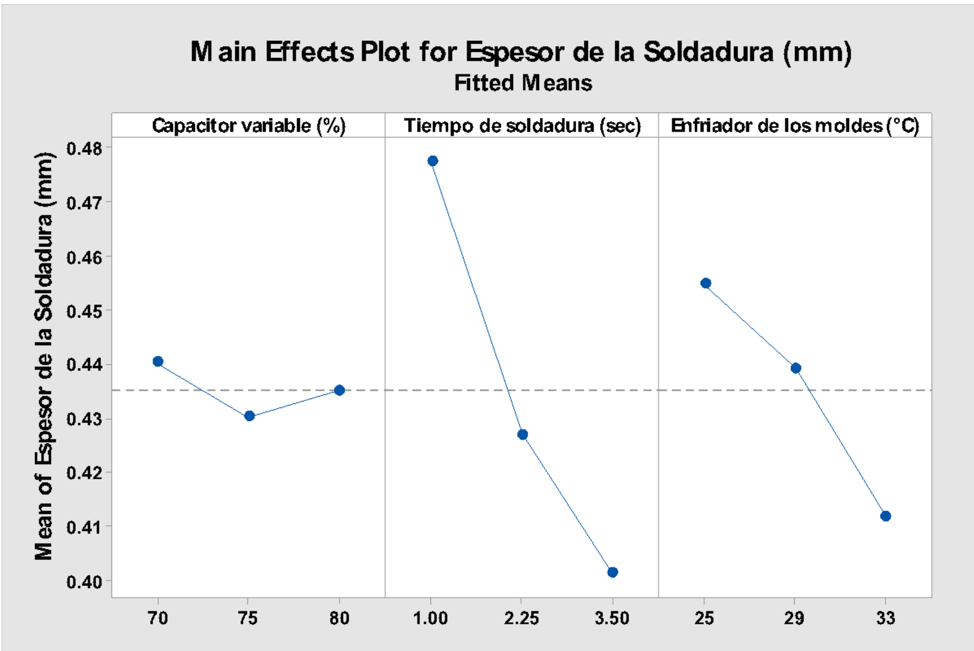


Figure 11. Main effects of the three significant variables

Note: Source: Author's creation.

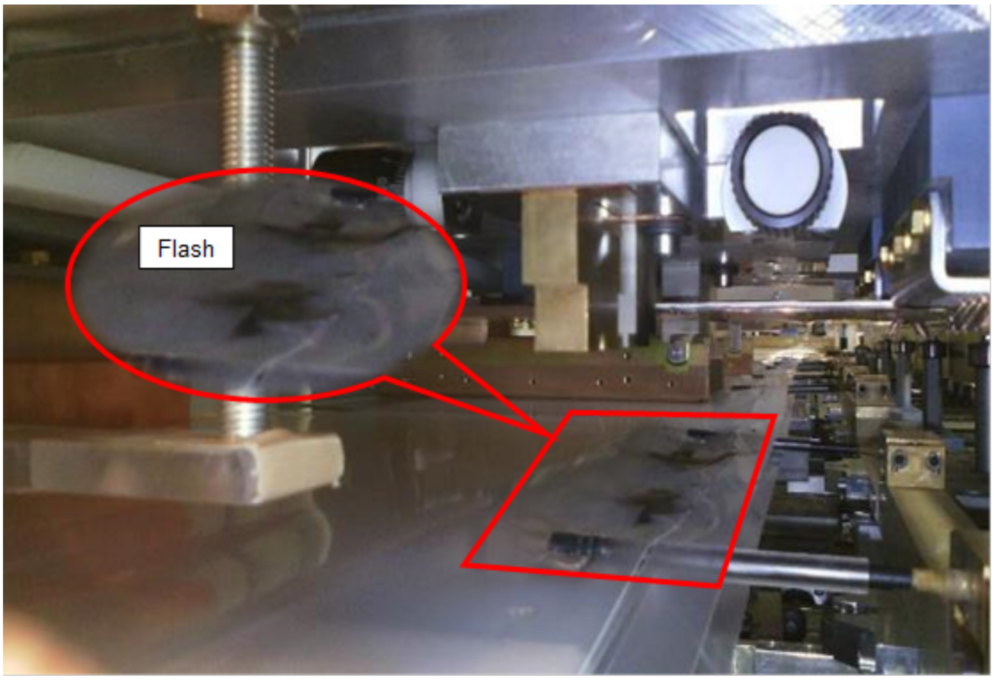


Figure 12. “Flash” effect on thickness specification welding

Note: Source: Author’s creation.

By analyzing Figure 13, it is possible to illustrate the interactions of the variables for the response, which is the thickness of the weld.

Within the three comparisons, we see that the combination that has the greatest interaction with the weld thickness is the temperature (°C) of molds cooling (electrodes) and the time of welding. This confirms the results obtained from the experimental designs and the analysis of the main effects graph. Statistically, it allows us to observe that the response of the thickness of the material, that is the fusion of the thermoplastic material, is proportional to the combination of the molds' temperature (electrodes), and the time of weld is greater, the effect of the thermoplastic material in arriving at T_m is aggressive. Figure 14 shows the melting of the thermoplastic material, but with an excess of material over the welding. Figure 15 shows the material welding, but with some measurements outside specifications (lower limit). Also, Figure 16 shows, by the visual inspection method, that the performance of the weld is not uniform, because it creates some flaws in the weld where the thermoplastic material is delaminated. In conclusion, the cooling time variable of the solder is not being efficient as the molds are hot. Besides, it affects the melting of the thermoplastic, having found that the EVOH material is a semi-crystalline thermoplastic. This effect is because the cooling time of the solder is responsible for cooling the solder made, to prevent the semi-crystalline thermoplastic material from continuing to increase the temperature and going beyond the T_m zone, where the effect is negative. After all, when passing this zone, the thermoplastic material goes into a liquid state affecting the quality of the solder.

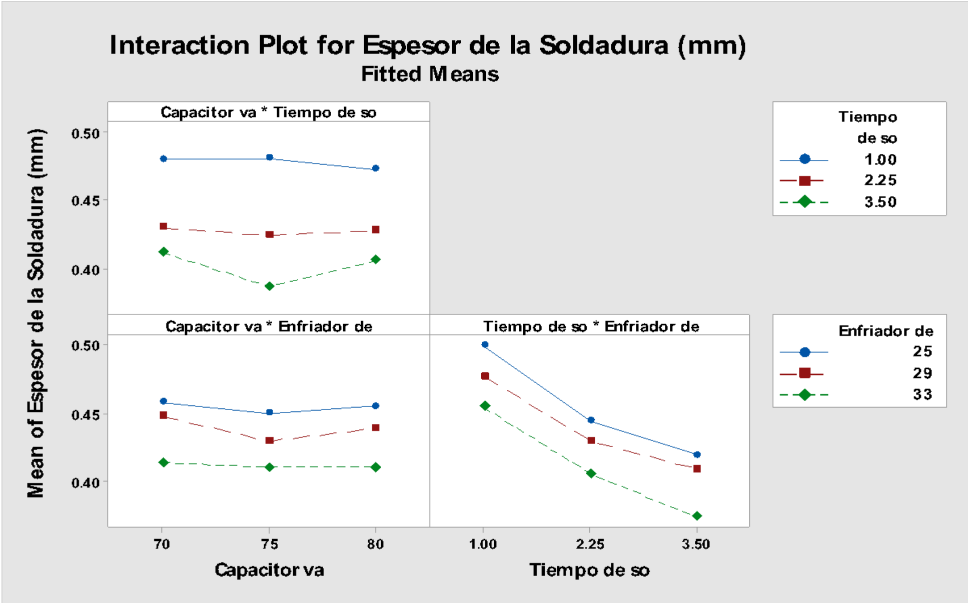


Figure 13. Interaction of the three significant variables

Note: Source: Author's creation.

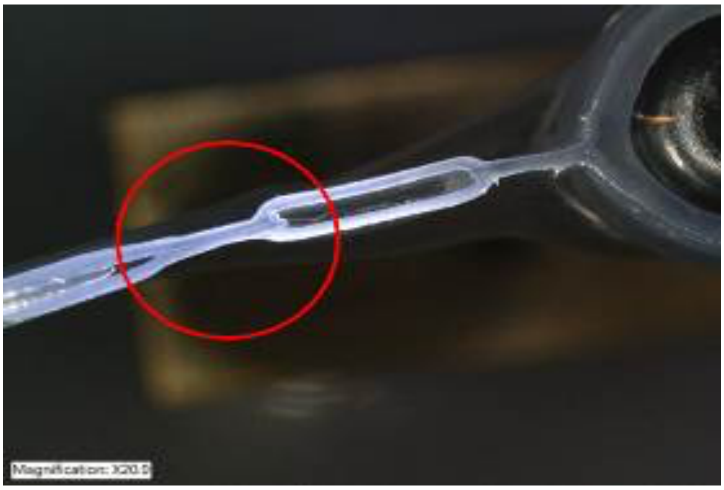


Figure 14. Material on weld with displaced material

Note: Source: Author's creation.

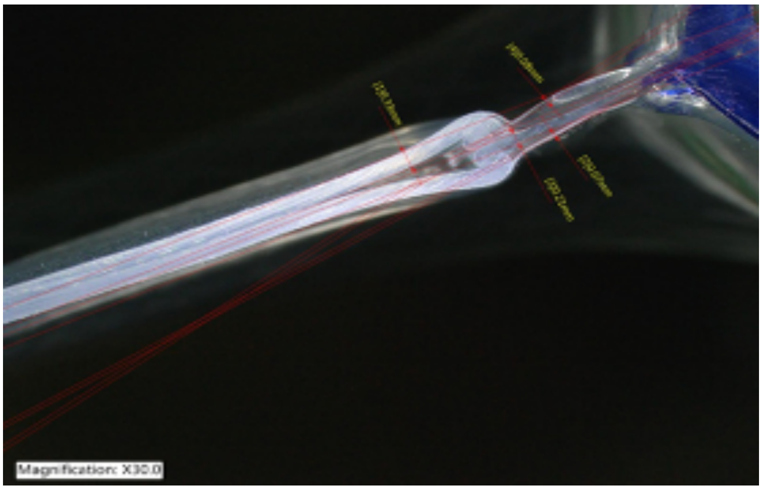


Figure 15. Measurements of material on weld

Note: Source: Author's creation.

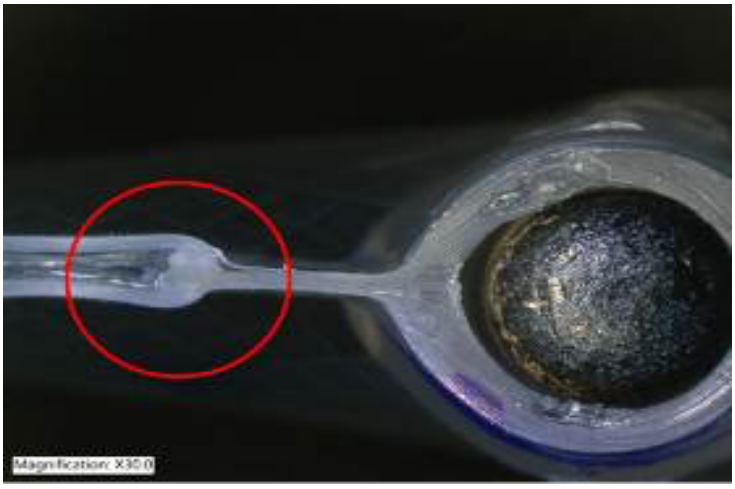


Figure 16. Welding rejected by visual inspection

Note: Source: Author's creation.

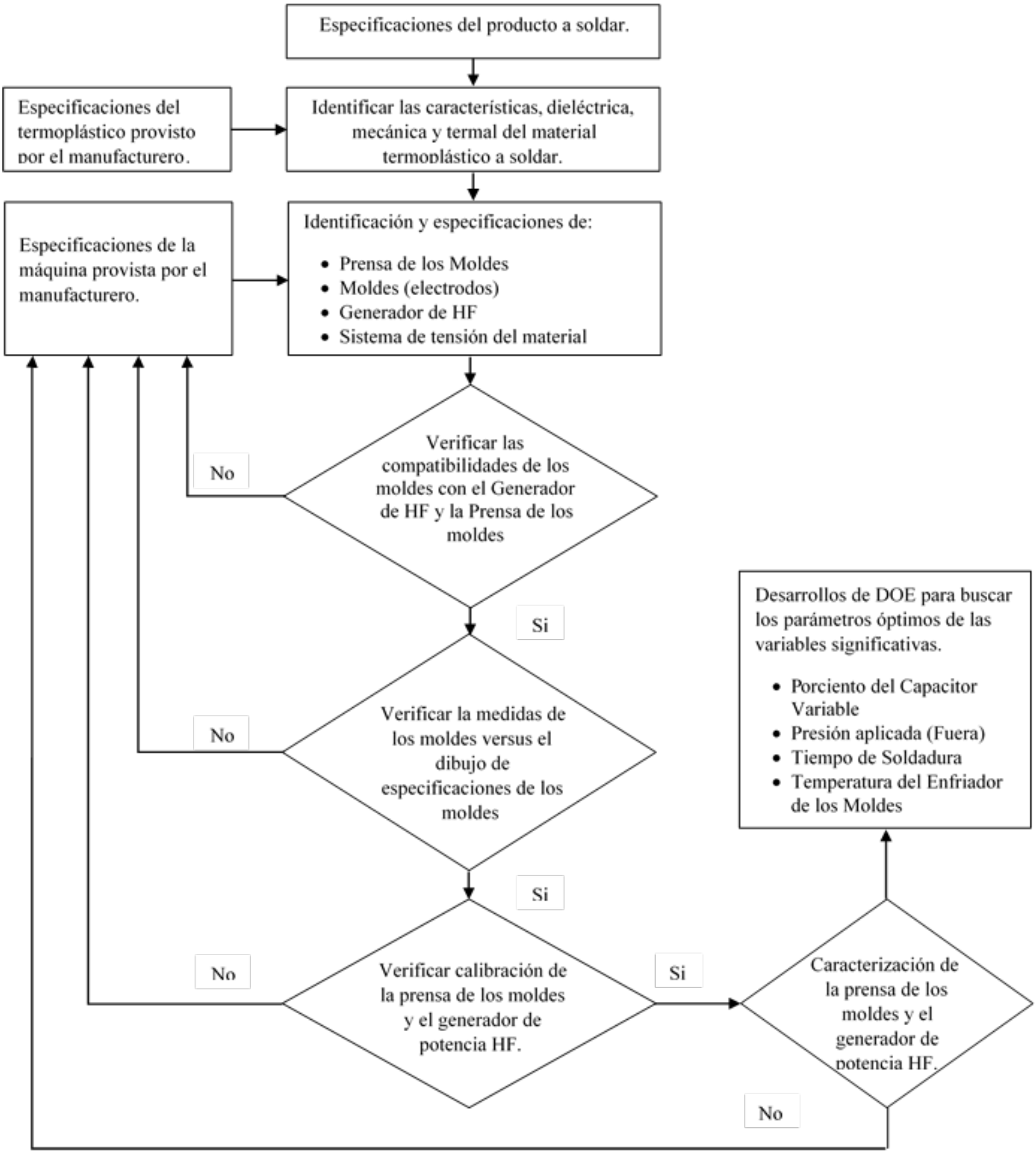


Figure 17. Methodology that enables the development of optimal processes for processes using high frequency (HF) technology.

Note: Source: Author's creation.

Results

Based on the results of the field research, the significant variables data was analyzed.

Parámetro	Valor Mínimo	Valor Promedio	Valor Máximo
Parámetro del % del capacitor variable	70 %	75 %	80 %
Tiempo de soldadura	1 sec.	2.25 sec.	3.5 sec.
Temperatura del enfriador de moldes	25 °C	29 °C	33 °C
Especificación del espesor del material soldado.	0.35 mm	0.40 mm	0.45 mm

Número de Experimento	Capacitor Variable (%)	Tiempo de Soldadura (sec.)	Enfriador de moldes (°C)	$\bar{X}$ de Espesor de Soldadura (mm)	Desviación Estándar (σ)
Experimento #27	70 %	2.25 sec.	33 °C	0.403 mm	0.015 (σ)
Experimento #25	75 %	3.5 sec.	25 °C	0.405 mm	0.010 (σ)
Experimento #7	80 %	3.5 sec.	29 °C	0.418 mm	0.013 (σ)
Experimento #26	70 %	3.5 sec.	29 °C	0.424 mm	0.014 (σ)
Experimento #1	75 %	2.25 sec.	29 °C	0.425 mm	0.012 (σ)
Experimento #15	80 %	3.5 sec.	25 °C	0.427 mm	0.013 (σ)
Experimento #21	70 %	3.5 sec.	25 °C	0.428 mm	0.007 (σ)
Experimento #12	70 %	2.25 sec.	29 °C	0.429 mm	0.015 (σ)
Experimento #22	80 %	2.25 sec.	25 °C	0.431 mm	0.008 (σ)

Figure 18. Summary of experiment designs

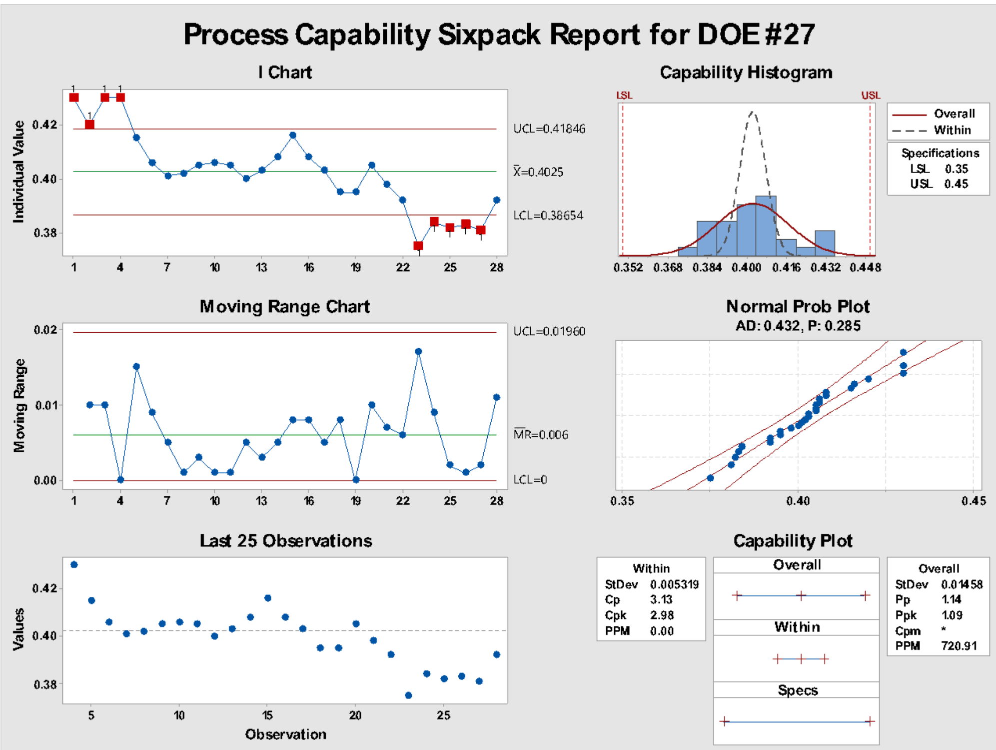


Figure 19. Experiment process capability #27

Note: Source: Author's creation.

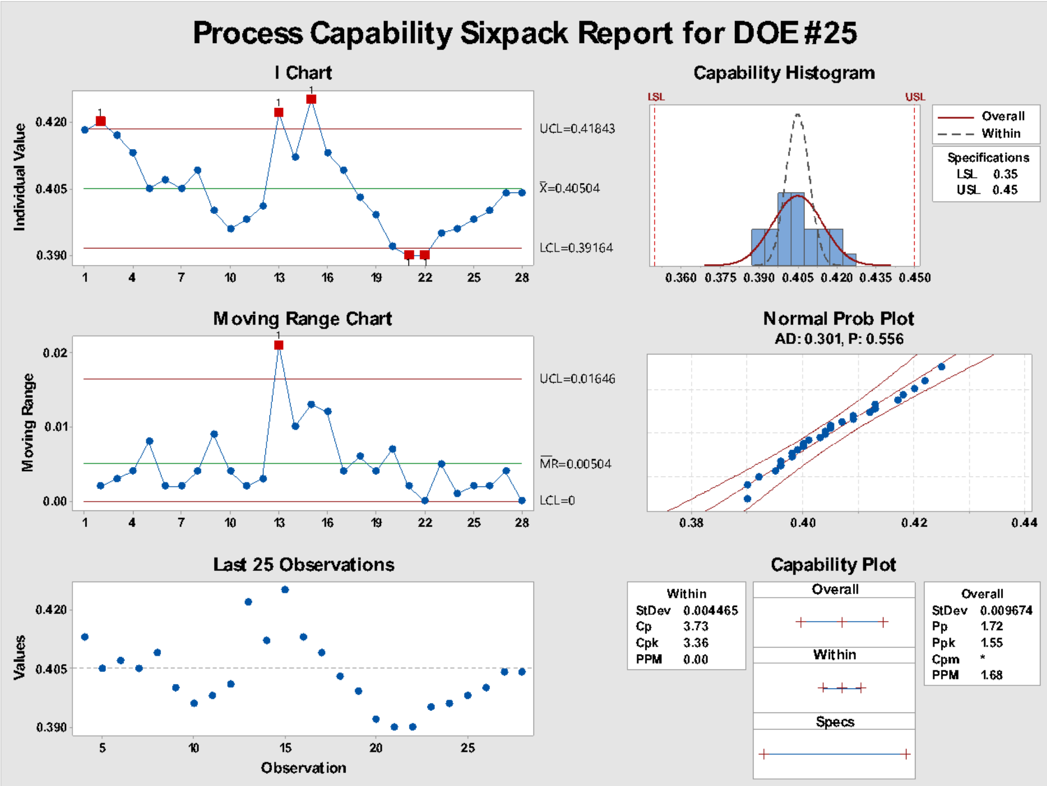


Figure 20. Experiment process capability #25

Note: Source: Author's creation.

Concluding with the results' information on the experiments carried out, nine out of twenty-seven experiments were obtained (Figure 18). In them, the acceptance criteria were fulfilled (visual inspection and dimensioning of the weld thickness). As a result of the nine experiments that met the acceptance criteria, there are two (experiments 27 and 25) that were accepted for the research and validation of parameters and processes. This is because one of the most important acceptance criteria is the average weld thickness and the two experiments had significant results, meeting the nominal value of the weld thickness specification (as shown in Figures 21 through 23) and allowing a range of adjustment in all three variables (Percent of Variable Capacitor, Welding Time and Mold Cooler Temperature) for process variations. And as a second important factor, standard deviations of 0.010 (σ) and 0.015 (σ) were obtained in the welding process of the thermoplastic material. Finally, experiment #27 shows in Figure 19 that the process had a Cpk of 2.98, and, in Figure 20, experiment #25 had a Cpk of 3.36. This leads to the methodology, where statistically it allows to obtain a 6 Sigma process, fulfilling a controlled, reliable, and predictable process.

Figure 21. Acceptable weld, tube release test versus EVA or EVA/EVOH layer

Note: Source: Author's creation.

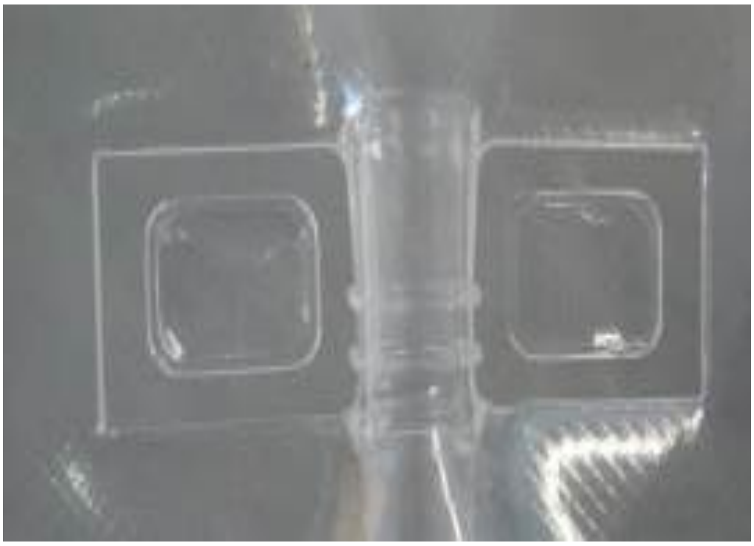


Figure 22. Acceptable weld, visual test

Note: Source: Author's creation.

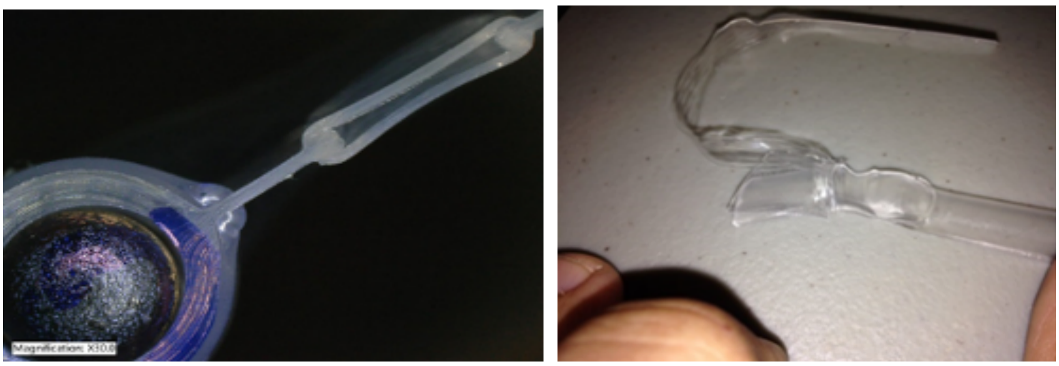


Figure 23. Acceptable weld, visual test and tube release test versus EVA or EVA/EVOH layer

Note: Source: Author's creation.

Discussion and conclusions

In the field research, it is concluded that, from the present work, it was observed that in different manufacturing companies in the manufacture of thermoplastic welding machines using a high frequency, an internal process is carried out to calculate the high frequency (HF) power generators based on their knowledge, technology, and experience. However, a standard methodology to start up the machine with the product is not carried out.

The parameters found from the characterizations and the designs of experiments differ in quantitative questions, for their different values, but in qualitative question, they are very similar. This is widely noticed in the characteristics of the force press and in the generators of high frequency, where it was predicted in which parts of the zone or process of the weld, the quality is going to be deficient. Besides, having conducted the welds varying the principal variables, it was observed that the variables indicated in experiment designs were present the ranges of parameters that influence directly in the principal defects.

The protocol proposed in the present work can be applied to obtain the most important parameters of the thermoplastic welding process with a high-frequency system in new electrodes (molds) or change of thermoplastic types. This is important since most of the time the electrodes (molds) are tested by changing the parameters randomly without a control, although it is necessary to use a lot of material in the application of the protocol. But in the end, you can identify the optimal values to use during production and you have a record of the defects found with different values in the parameters. Also, it is a tool that will help optimize the process.

In comparison with the work experience against the protocol, in the first one, it is possible to obtain acceptable parts in all aspects and without the use of much materials. Figure 17 shows a flow chart that was developed during the research, providing support to get a strong process. Where it is possible to develop optimal processes for processes using high frequency (HF) technology.

The disadvantages of scientific molding are the use of a lot of material for testing and the time spent on it. We can add the fact that scientific molding cannot be fully applied with engineering thermoplastic materials.

Statistical analysis serves to identify the variables that affect the part in a quantitative way. This is important since it is not based on the operator experience.

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