Study of resistance welding consumables: Research of new materials and development of the methodological standard

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Master Dissertation

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To my girlfriend, family, and friends for their unwavering support…

Abstract

Resistance projection welding is a widely employed industrial technique in the automotive sector, offering strong and durable welds. However, the method's high consumable and energy requirements pose significant challenges for manufacturers. This study addresses the growing need to develop novel materials for resistance welding consumables to reduce energy usage, costs, and waste.

Gestamp Cerveira, a prominent supplier of metallic components for the automobile industry, recognizes the importance of minimizing energy consumption, expenses, and the environmental impact associated with resistance welding. To achieve these goals, the organization has invested in research and development efforts to explore new materials for resistance welding consumables.

Building upon prior research on optimizing welding parameters, a study conducted by Mariana Souto identified a promising opportunity related to electrode materials. Analysis of the welding equipment setup revealed that the electrical conductivity of the electrode was considerably lower than that of the supporting part, resulting in increased circuit resistance. It was proposed that an electrode with improved conductivity would enhance efficiency.

Through a series of experiments, several internal wear paradigms were changed, and the AMPCOLOY 972 material was selected as the proposed solution, considering its conductivity over hardness characteristics. Following a conservative welding parameter optimization, significant improvements were observed, including cost savings of approximately 2620€/year, a 13% reduction in power consumption, and a notable decrease in electrode waste.

In addition to the proposed solution, a set of guidelines was presented to assist future studies and the implementation of this optimization approach on other welding equipment within the company. By adopting these guidelines, Gestamp Cerveira aims to propagate the benefits achieved and further enhance their resistance welding processes.

This case study exemplifies the potential for optimizing resistance welding consumables to achieve improved energy efficiency, cost reduction, and waste minimization in the automotive industry. The findings provide valuable insights for manufacturers seeking to enhance their welding operations while prioritizing environmental sustainability

Resumo

A soldadura por projeção por resistência é uma técnica amplamente empregada na indústria automóvel, oferecendo soldaduras robustas e duráveis. No entanto, os elevados requisitos de consumo de consumíveis (elétrodos) e energia associados a este método representam desafios significativos para os fabricantes. Este estudo aborda a necessidade crescente de desenvolver novos materiais para consumíveis de soldadura por resistência, visando reduzir o consumo de energia, os custos e o desperdício.

A Gestamp Cerveira, um fornecedor proeminente de componentes metálicos para a indústria automóvel, reconhece a importância de minimizar o consumo de energia, as despesas e o impacto ambiental associados à soldadura por resistência. Para alcançar esses objetivos, a organização tem investido em esforços de investigação e desenvolvimento para explorar novos materiais para consumíveis de soldadura por resistência.

Com base em pesquisas anteriores sobre a otimização de parâmetros de soldadura, um estudo conduzido pela Engª Mariana Souto identificou uma oportunidade promissora relacionada aos materiais dos elétrodos. A análise da configuração de um equipamento de soldadura revelou que a condutividade elétrica do elétrodo era consideravelmente inferior à da peça que o sustentava, resultando em um aumento da resistência do circuito e consequente dissipação de energia. Surgindo assim este projeto cujo objetivo consiste em estudar e propor novos materiais para os consumíveis de soldadura e desenvolver um standard metodológico para propagar a sua aplicação às restantes máquinas.

Por meio de uma série de experiências, vários paradigmas internos de desgaste foram modificados, sendo selecionado o material AMPCOLOY 972 como a solução proposta, tendo em consideração suas características de condutividade e dureza. Após uma otimização conservadora dos parâmetros de soldadura, foram observadas melhorias significativas, incluindo uma economia de custos de aproximadamente 2620€/ano, uma redução de 13% no consumo de energia e uma notável diminuição do desperdício de elétrodos.

Além da solução proposta, um conjunto de diretrizes foi apresentada para auxiliar estudos futuros e a implementação dessa abordagem de otimização em outros equipamentos de soldadura dentro da empresa. Ao adotar essas diretrizes, a Gestamp Cerveira tem como objetivo propagar os benefícios alcançados e aprimorar ainda mais seus processos de soldadura por resistência.

Este estudo exemplifica o potencial de otimização de consumíveis de soldadura por resistência para obter uma maior eficiência energética, redução de custos e minimização de desperdícios na indústria automóvel. Os resultados fornecem *insights* valiosos para os fabricantes que procurem aprimorar suas operações de soldadura, ao mesmo tempo em que priorizam a sustentabilidade ambiental.

Acknowledgments

I would like to express my sincere gratitude and appreciation to Gestamp Cerveira for their collaboration, support, and commitment to improving resistance welding processes in the automotive sector. Their valuable insights, access to industry knowledge, and provision of resources were instrumental in the successful execution of this study.

Special thanks are extended to Dr. Gonçalo Cipriano and Eng.a Mariana Souto for serving as my mentors throughout this research endeavour. Their guidance, expertise, and invaluable insights significantly influenced the direction, methodology, and outcomes of this study. His continuous support and constructive feedback were instrumental in shaping the quality and rigor of this work.

I would also like to express my appreciation to the individuals who willingly contributed their time, expertise, and patience to this study. Their involvement in the experiments, data collection, and insightful discussions played a crucial role in the generation of meaningful results and the overall success of this research.

Furthermore, I extend my gratitude to the Faculty of Engineering of the University of Porto (FEUP) and the Institute of Mechanical Engineering and Industrial Management (INEGI) for their collaboration and support throughout this research project. Their expertise and resources were instrumental in the successful execution of this study.

I am deeply thankful to my friends, girlfriend, and family for their unwavering support, understanding, and motivation throughout this journey. Their belief in me and their constant encouragement provided the strength and inspiration needed to overcome challenges and achieve the goals of this study.

To all those who have contributed to this research project, directly or indirectly, your support and involvement are deeply appreciated and acknowledged.

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Acronyms

AENOR - Asociación Española de Normalización y Certificación / Spanish Association for Standardization and Certification

Al - Chemical symbol for the element Aluminium

ANOVA – Analysis of Variance

CNC – Computer Numerical Control

Cu - Chemical symbol for the element Copper

DOE – Design of Experiments

Fe - chemical symbol for the element Iron

FEUP – Faculdade de Engenharia da Universidade do Porto / Faculty of Engineering at the University of Porto

I - electrical current (Amper)

IACS - International Association of Classification Societies

IATF - International Automotive Task Force

INEGI - Instituto de Ciência e Inovação em Engenharia Mecânica e Engenharia Industrial / Institute of Science and Innovation in Mechanical Engineering and Industrial Engineering

ISO – International Organization for Standardization

PW - Projection welding

Q - Power generated (Watt)

R – Electrical Resistance (ohm)

RSW – Resistance Spot Welding

S/N – Signal to Noise ratio

TMAZ – Thermomechanical Heat Affected Zone

t – Time (seconds)

Zn - chemical symbol for the element Zinc

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1 Introduction

1.1 Context and motivation

Resistance welding is a common industrial technology that plays a vital part in the automotive sector. The method involves applying pressure and an electrical current through an electrode to unite two or more metal parts (Kimchi and Phillips 2017). Although this method is highly effective at producing strong and long-lasting welds, it is also extremely consumable- and energy-intensive, resulting in substantial expenditures for producers (Kimchi and Phillips 2017). As a result, there is a rising need to create novel materials for resistance welding consumables that can aid in reducing energy usage, prices, and waste.

Gestamp Cerveira, a leading supplier of metallic parts and components to the automobile industry, acknowledges the significance of decreasing resistance welding's energy usage, prices, and consumables. The organization is committed to offering high-quality products to its consumers while minimizing its environmental effect. Gestamp Cerveira has invested in research and development to explore new materials that may be utilized for resistance welding consumables in order to reach these objectives.

1.2 Gestamp Cerveira

Gestamp Cerveira, Lda. is affiliated with the Spanish corporation Corporación Gestamp. Figure 1 depicts the logos of this group's three primary companies: Gonvarri Steel Industries, Gestamp Automoción, and Gestamp Renewables. Their respective primary businesses are the manufacturing of steel, metallic components for the automotive sector, and renewable energies. Gescrap, another company affiliated with the group, is responsible for the transportation and handling of the scrap produced by the group's stamping factories.

Figure 1 – Gestamp company logos: Gonvarri Steel Industries, Gestamp Automoción and Gestamp Renewables (Gestamp Cerveira 2023a)

Gestamp Cerveira, Lda., which specializes in stamping and welding, is one of Gestamp Automoción's plants. The corporation is responsible for more than one hundred plants located in twenty-four countries. Its primary activity is the production of body-in-white (BIW) chassis, and mechanisms for use in automobiles, and its primary goal, in line with that of the automotive industry as a whole, is to lower the weight of vehicles while ensuring the quality and safety of their components. Figure 2 depicts some examples of the components made by Gestamp Cerveira.

Figure 2 – Corporation Gestamp's production portfolio (Gestamp Cerveira 2023a)

This factory in Vila Nova de Cerveira is near to Portugal's northern border. From 1995 to 2008, Gestamp Cerveira (known as Gestamp Portugal until 2013) was dependent on Gestamp Vigo during its formative years. With internal reform and the development of the appropriate divisions in 2008, the plant became entirely independent and autonomous, with autonomous administration and decision-making processes. Yet, the relationship between the two factories continues to be strong. In 2013, the factory's name was changed from Gestamp Portugal to Gestamp Cerveira, as there were already three Gestamp facilities in Portugal, located in Vila Nova de Cerveira, Vendas Novas, and Aveiro.

Figure 3 illustrates the development of the human resources. In 2019, 647 individuals were employed in Gestamp Cereira. By 2021, due to the COVID-19 pandemic, this number had decreased to 494 individuals. Notwithstanding this downsizing, this factory continues to play an essential role in the regional economy. 44% of the 494 employees are female, while 56% are male.

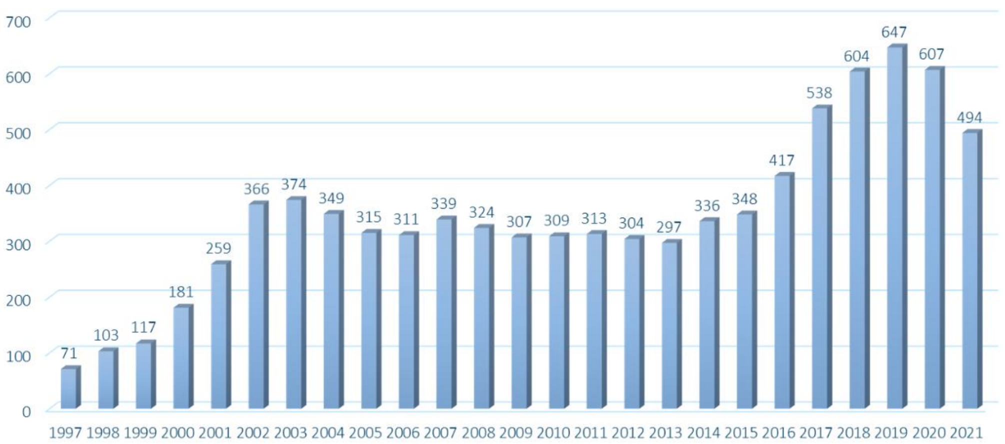


Figure 3 – Evolution of turnover at Gestamp Cerveira (Gestamp Cerveira 2021)

As depicted in Figure 4, certifications have been granted to this factory over the years. Among these certifications are ISO 9001, ISO/TS 16949, ISO 14001, EMAS, "Resduo Zero" AENOR, and ISO 45001 in the fields of health and safety, quality, and the environment. In 2014, 2015, 2016, and 2017, PSA– Peugeot Citroen S.A. (now Stellantis) also awarded it with the "Best Factory" award.

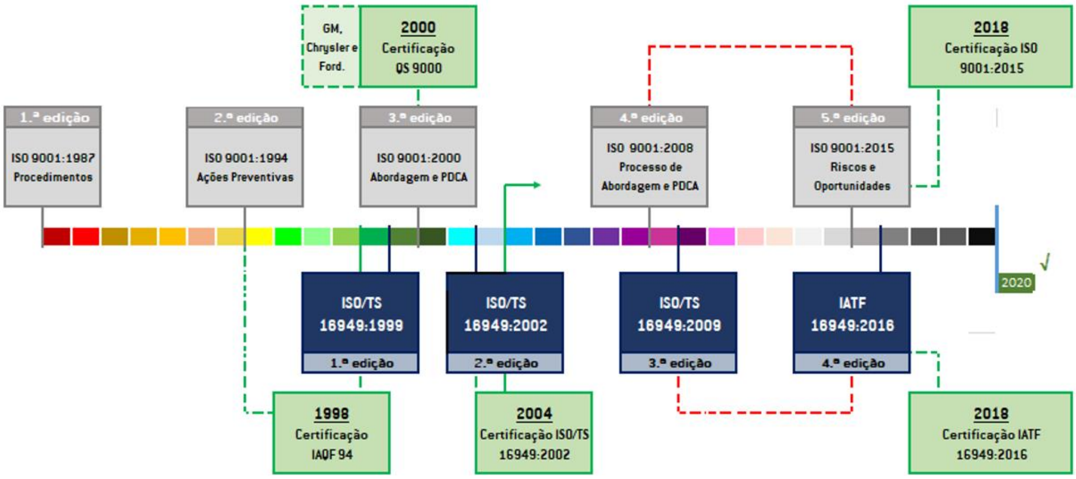


Figure 4 – Figure of important milestones (Gestamp Cerveira 2021)

The clients of Gestamp Cerveira are both internal and external. These correspond to non-Gestamp factories such as Stellantis (former PSA), Renault/Nissan, Volkswagen, and others. Figure 5 illustrates Gestamp Cerveira's major clients. A significant portion of Gestamp Cerveira's output does not go directly to the client that assembles automobiles. Part of this production is sent to intern clients, i.e., other Gestamp plants, for further manufacturing or assembly.

Figure 5 – Main clients of Gestamp Cerveira (Gestamp Cerveira 2023a)

1.3 Objectives

This work was developed mostly by Gestamp Cerveira, Lda in close collaboration with Institute of Science and Innovation in Mechanical Engineering and Industrial Engineering (INEGI). Being a dissertation prepared in an industrial setting, one of the primary goals is to generate a comprehensive, organized, and relevant study that can contribute to the success of the project in which I am participating and, in turn, benefit the organization. Consequently, the primary purpose is to select the best materials in order to increase the company's financial savings, enhance the quality of the welding, and reduce the environmental impact. Many tasks are required to accomplish this goal.

This industrial environment provides additional hurdles to begin with. When I began my internship, my first duty was to gain a thorough understanding of the company's structure, procedures, clients, suppliers, organization, and the individuals who would be responsible for the operation and execution of part of the work.

Regarding the technical tasks, I was unable to specify them until my integration into the organization was well established and I was aware of the department's challenges and duties. Once integrated, the project was proposed.

To satisfy the major objective of this dissertation/project, the tasks or actions that must be done during this work are:

- Acquire a deep understanding of the resistance welding process, specifically the Projection Welding;
- Closely follow and study the manufacturing process and all the nuances involved at the factory floor;
- Detailed characterization of the requirements and specifications of the electrodes used in projection welding;
- Deeply understand electrode's materials, standards and suppliers;
- Conduct investigations and experiments to validate the selection of new materials;
- Proposing alternative materials and process improvements;
- Test electrodes made of alternative materials and optimize welding parameters;
- Conduct investigations and experiments to evaluate the differences between the chosen material and the previous one;
- Make the energy, economic, and sustainable balance sheet account for the improvements;
- Develop a methodological standard that can be used to apply the proposed change to another 19 machines and make the gains even bigger.

1.4 Methodology

As previously said, since this dissertation is developed in an industrial context, the initial weeks require a comprehensive understanding of the company's procedures, clients, suppliers, departments, organization, and personnel.

After that, a better understanding of the manufacturing process is required. During this stage, it is important to closely follow all the steps taken by the operators while producing the joints using the welding equipment. At the same time, there should be a structured and systematic review of projection welding to fully understand the processes seen on the shop floor. Once understood, it is necessary to critically examine the process to identify potential flaws, details and improvements that may be important for the project, especially those related to the electrodes.

Once the details and specifications of the process are characterized, investigations and experiments are conducted to validate the material selection. Following the electrode's material selection, its performance is analysed and optimized through experiments aimed at assessing differences between the currently used and chosen alternative materials. Subsequently, a methodological standard is developed in the most efficient way to propagate the benefits easily to other machines and escalate the gains. Throughout the development of this dissertation within the company, all experiments are closely supervised to ensure that decisions are firmly justified.

Figure 6 depicts a Gantt chart that shows how the time needed for each task is split up. This helps to summarize and understand the project's method.

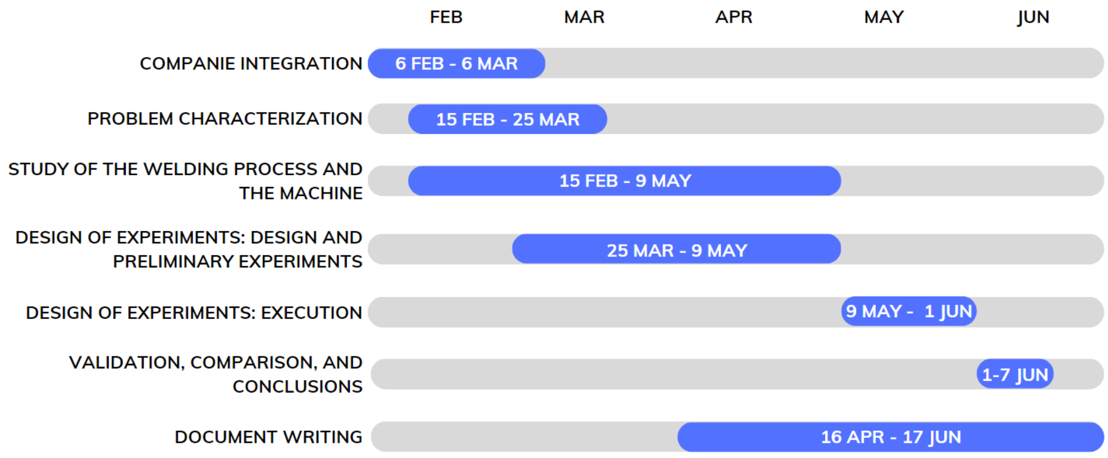


Figure 6 – Gantt´s diagram of activities to be carried out within the scope of the project.

1.5 Structure and layout

This thesis aims to select the best materials so as to raise the company's financial savings, improve the quality of the welding, and minimize its environmental impact. Besides studying the actual process and suggesting a new alternative material to be used as electrode, it also intends to develop a methodological standard that can be used to apply the proposed change to another 19 machines.

In addition to the current chapter (Chapter 1), which provides a brief introduction to the company, the driving forces of this project, and a general methodology overview, this thesis consists of five other chapters and appendices.

Chapter 2 presents some fundamentals and basic concepts on the technologies and methods that were studied during this thesis: resistance welding (projection welding), thermomechanical heat affected zone (TMAZ), the universe of the electrode's materials, and the statistical optimization Taguchi´s method.

Chapter 3 is focused on the project proposed in detail. A review of the part, its manufacturing process, its mechanical requirements, and its application is done. Ending with a detailed description of the problem proposed.

Chapter 4 describes the proposed solution to the problem/project. At first, the process that led to the new electrode's material selection. This stage includes the experiments, the investigations, and the justifications that validate the proposed solution. Then its application in the manufacturing process, where some studies have been made like welding parameters optimization (statistical approach), and a comparative with the previous material considering several indicators and measurements.

Chapter 5 presents a methodological standard that can be used to implement the proposed change on an additional 19 machines to increase the gains.

Finally, Chapter 6 presents the main conclusions of this thesis, along with some perspectives and suggestions for future work.

2 State-of-the-art

2.1 Projection welding

The welding processes can be divided into material fusion welding and solid-state welding (Zhang and Senkara 2011). Within the processes of welding by fusion of material, electrical arc welding, laser welding, and resistance welding are highlighted, with the first being carried out by adding material and the remaining not considering the addition of material. Resistance welding is a process widely used in the automotive industry for the joining of plates and components due to its ease of adaptation to different materials and joint conjugations, relatively low cycle time and cost, and the possibility of being automated (Shafee, Naik, and Sammaiah 2015).

There are more 5000 welded joints in a car, with a significant number of them located in the structural components, making them crucial for the car's integrity (Janardhan, Mukhopadhyay, and Dutta 2022). Ensuring the effectiveness of this bonding process is of utmost importance (Summerville, Compston, and Doolan 2019). Resistance welding, one of the oldest welding methods, offers fast, efficient, and environmentally friendly approaches without the need for filler materials. However, it has potential drawbacks such as a high initial cost and a limited range of applications (Shane 2023). The principle of resistance welding involves passing an electric current through the resistance formed by the contact of two metal surfaces, generating heat during the process The current density is sufficiently high to create a localized pool of molten metal, effectively fusing the two pieces together. Typically, the current ranges between 1000 and 100,000 A, while the voltage falls within the range of 1 to 30 V (Weman 2003).

Projection welding (PW), schematically illustrated in Figure 7, is a form of resistance welding in which the current flow is concentrated at the point of contact with a local geometric extension of one or both of the pieces being welded (Zhang and Senkara 2011). The purpose of these extensions or projections is to concentrate heat generation at the point of contact. In general, the process requires lower currents, lower forces, and shorter welding times than a comparable application without projections. Projection welding is frequently used in the most difficult resistance-welding applications because multiple welds can be made simultaneously, thereby accelerating the production process (Committee and Metals 1982).

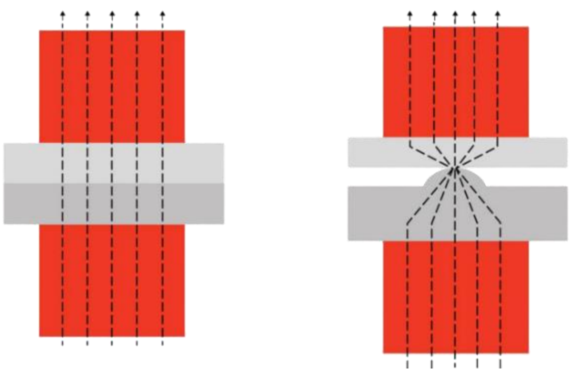


Figure 7 – Schematic representation of welding current flow concentration due to projection geometry (AISBL 2020).

In general, PW applications are classified as either embossed projection welding or solid projection welding. These variants are depicted in Figures 8 a) and b). Embossed-projection welding (Figure 8 a)) is typically a sheet-to-sheet joining process that involves stamping a projection onto one of the sheets to be joined. Then, a stack of sheets is subjected to resistance welding. Initially, heat concentrates at the contact point and along the walls of the projection during resistance welding. The projection itself collapses back into the original sheet early in the process. Nevertheless, the initial heating increases the local resistivity of the joint area, allowing resistance heating to continue at this location. The development of the weld then continues in the conventional manner, with the formation of a weld nugget (Committee and Metals 1982; Mikno 2016).

Solid-projection welding (Figure 8 b)) requires the forging of the projection onto one of the two components. The contact point and the projection itself experience preferential heating during resistance welding. As opposed to embossed-projection welding, the projection in this instance cannot simply collapse. Rather, the projection collapses through penetration of the opposing material and extrusion to the periphery. In contrast to embossed-projection welding, the resultant joints are solid-state welds. Similar to resistance butting and flash butting welding, the actual joints are the result of a combination of material forging and diffusion bonding (Committee and Metals 1982; Sejč et al. 2020).

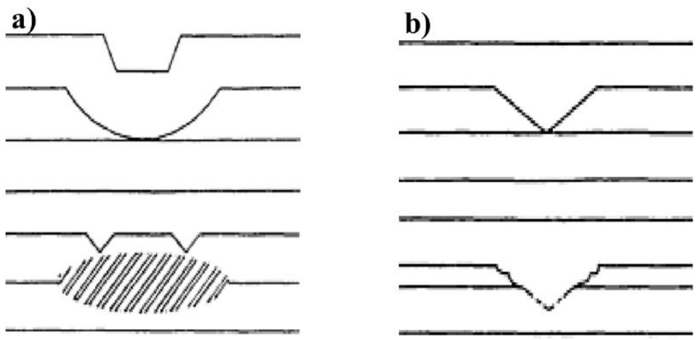


Figure 8 – Representation of typical stacked configuration for: a) embossed-projection welding; and b) solid-projection welding (Committee and Metals 1982).

The main welding process parameters are the welding current and time, the electrode pressure, and the cooling temperature and flow (Sun 2000). In addition, there are many other factors that have an influence on the welding process, including: the geometry, material, and coating of the components to be welded; the geometry and material of the electrodes; the surrounding environmental conditions; cooling conditions, among others (Zhang and Senkara 2011). A better understanding of the specifics and impacts of each parameter is so important that a section of this work has been dedicated to it. Before that, in the following two chapters, the advantages and disadvantages of PW compared with other welding technologies will be presented (Shane 2023; Zhang and Senkara 2011; Committee and Metals 1982).

2.1.1 PW advantages:

- Multiple welding spots can be welded in a single procedure, with the only limitation being the ability to control the current and force.
- Projection welding makes it possible to weld narrow flanges due to its high current concentration, limited shunting opportunities at the welding spot, and closer welding spot spacing than spot welding.
- The electrode contact surface in projection welding is larger than its projection and also larger than the electrode contact surface used in spot welding with the same nugget diameter, resulting in less electrode maintenance as a result of the reduced current density.
- Metals that are too thick for resistance spot welding (RSW) connections can be joined using projection welding.
- The size and position of the projection can be chosen flexibly, allowing for a thickness ratio of 6 (or greater) to 1 between the projection and the workpiece. This can be challenging to accomplish with spot welding for pieces with a thickness ratio of approximately 3:1.
- The method can be used to create junctions that are impervious to leaks, such as ring projection welding.

2.1.2 PW disadvantage:

- Forming one or more protrusions on a workpiece will necessitate additional operations unless the component can be pressed into the desired shape.
- When using the same electrode to weld multiple solder joints simultaneously, the alignment of the workpiece and the control of the protrusion size (especially its height) must be maintained within strict tolerances to ensure uniform quality of the solder joint.
- When conducting simultaneous projection welding of multiple solder joints, the distribution of the projection may not align with the desired position due to the current's shunt path.

2.1.3 Influence of welding parameters and other factors on PW

2.1.3.1 Heat generation – Joule's Law

As previously said, there are several parameters and factors that influence the welding process. Starting with the main welding parameters, the most critical ones in the PW welding process are the welding current, the welding time and electrode's pressure force. The influence of the first two is understandable since these are related to the heat generated according to Joule's Law, expressed by equation (2.1), where Q represents the power generated in joules, R the electrical resistance in Ohms, I the electric current in Amper, and the t for welding time in seconds (the total time during which the current flowed) (Sejč et al. 2020).

$$Q = R \cdot I^2 \cdot t \qquad [\mathrm{J}] \tag{2.1}$$

In spite of being considered the main parameters, they have different relevance. It should be noted that the intensity of the current arises from a power of two, so that, of course, is the parameter that contributes the most to the heat generated by resistance, and it is easily adjustable. In turn, the resistance (R) depends on the materials to be welded, so in most cases it is not a parameter that can be manipulated. Both the resistance and the welding time are directly proportional to the power generated, so when these increase, naturally, the power generated increases.

The current could be applied in several ways (peak, gradually, in stairs, etc.), and the time can be manipulated in different ways. However, in practice, for PW, as Furusako et al. (2019) concluded, the impact of welding time and the type of application of the current is not as significant as initially envisioned.

2.1.3.2 Welding pressure force

The force exerted by the electrodes on the components to be joined is considered one of the main parameters in PW. It's important that the projections have a good settlement, enough penetration (when necessary), and that collapse correctly occur (Sun 2000; Committee and Metals 1982; Mikno 2016). The welding equipment should ensure that the projections receive the appropriate force rapidly and that the force can be maintained as the projections collapse (severe local plastic deformation of the projection due to material softening and pressure forces). If the force application fails or is not constant the integrity and quality of the produced weld can be compromised (Mikno 2016).

The electrode's force is usually applied using pneumatic systems due to their low complexity, maintenance, and associated cost. However, these systems are known to have high response inertia and struggle to maintain a specific force during the weld, which is exactly the opposite of what is recommended. To control this problem, the manufacturers oversized the pressure force to assure that during the collapse, when the force decreases, it is at least, around the desired force. Nevertheless, this increased force that compensates for the response inertia causes another problem, which is an excessive collapse of the projection during the welding cycle that leads to a type of weld that is formed from the outer diameter inwards. This type of welding is not only more difficult to predict and control, but also consumes more energy since the electrical resistances are lower and it requires higher current and time to execute the weld. (Mikno 2016)

Moreover, as Furusako et al. (2019) stated, in some scenarios the pressure force is the parameter that most heavily influences the welding in PW. A variation in the load has a greater impact than a variation in current or welding time. They experimentally concluded how the pressure force variation influences the load that the weld can sustain when tested. They observed that for lower forces, where the relation between parameters has a peak, it is possible to achieve higher failure loads with less current (less energy consumption), even though it is more difficult to find the right current. For higher forces, on the other hand, the relation between parameters is closer to being proportional. As the current increases, the failure load also increases. Note that these conclusions are made for that specific case. Despite the fact that they cannot be generalized, they are important to understand the phenomena involved in PW and to define possible experimental tests.

Based on the knowledge acquired, this phenomenon can be explained as follows:

- For higher forces, Figure 9, as the weld is produced from the outside to the inside due to excessive collapse (Figure 9 a)), increasing the current will naturally increase the heat generation, and then the interior zone, still not softened/melted will reduce and, at the limit, disappear (Figure 9 b)). In this case, the weld is a mixture of solid-state welding (forged) and molten-state welding (fusion).

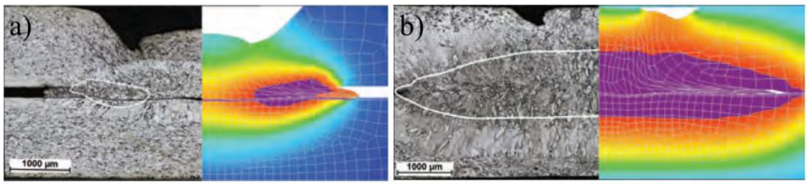


Figure 9 – a) Initial steps of projection welding under high welding forces; b) Last steps of projection welding under high welding forces (Mikno 2016).

- For lower forces, Figure 10, the collapse of the projections will depend on the melting and softening of the projections. In this case, since the overall electrical resistance (lower contact area) is higher, the heating generated will be higher, and the projections will melt on the contact points and the projection will gradually collapse/deform, leading to a weld from the inside to the outside. Then, when comparing this with the same current for higher forces, for this case the weld will be more consistent, leading to more reliable higher failure loads.

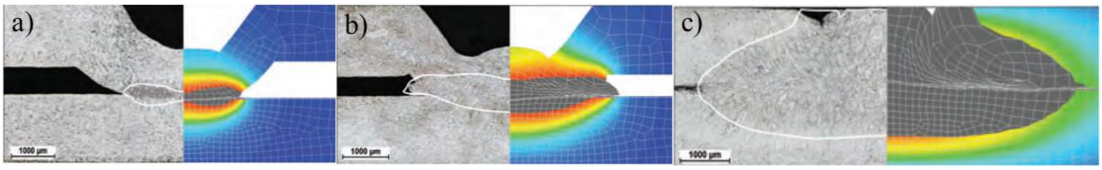


Figure 10 - a) Initial steps of projection welding under lower welding forces; b) Intermediate steps of projection welding under lower welding forces; c) Last steps of projection welding under lower welding forces (Mikno 2016).

The correlations between the parameters peak for the lower forces, since the quality of the weld is highly dependent on the melting of the materials and expulsion defects, and consequently, this is highly sensitive to current variations. If the current is slightly lower, the melting will not properly occur, and if the current is slightly higher, expulsion as flash material will occur and melted material will escape from the weld, making it weak. On the other hand, for higher loads, once the quality of the weld depends on the size of the softened/melted area, which is directly correlated with the heat input. The relationship between the current and the weld quality is proportional until a maximum occurs (all the material has softened or melted).

2.1.3.3 Materials

The materials involved in the welding are crucial to its successful production and mechanical performance. In essence, solid-projection welds are strain-assisted diffusion connections (Zhang and Senkara 2011). Due to the fact that the projections completely deformed at considerably high temperatures (for metals typically within a few hundred degrees Celsius of the melting point) and diffusion bonding can occur within the extremely brief available time (usually less than 1 s). Therefore, some of the same material-related factors that influence diffusion bonding also influence solid-projection welding. The most significant of these is the metal's ability to dissolve its own oxide. Given this, projection welding will be comparatively challenging for materials that do not energetically favour the solid solubility of oxygen over the formation of the oxide at forging temperatures(Sejč et al. 2020; Committee and Metals 1982) .

Besides diffusion bonding, there are other two important factors that heavily influence PW. The strength-temperature relationship and bulk resistivity. Materials that retain their strength at relatively high temperatures allow for considerable heating to occur prior to projection collapse. This heat is then available to facilitate diffusion following the collapse of the projection. Premature collapse results in lower temperatures at which diffusion can occur, as well as diminished current density, which prevents further resistance heating. Bulk resistivity also plays a role, albeit to a lesser extent, in projection welding. Increased bulk resistivity can diminish a projection's efficacy as a current concentrator. With increasing bulk resistivity, delocalized heating and a general rather than local collapse of the projection is more likely to occur. High-resistivity materials are consequently more difficult to projection weld (Zhang and Senkara 2011; Committee and Metals 1982).

Mild steels and low-alloy, nickel-based alloys are optimal for projection welding given that these dissolves their own oxides readily and have adequate strength, temperature, and resistivity properties. Due to the formation of more stable chromium and aluminium oxides, increased high-temperature properties, and higher resistivities, stainless steels and higher-alloy nickel-base materials become marginally more challenging to weld (Committee and Metals 1982).

2.1.3.4 Coatings

The coating is another issue that often comes up when steel is welded in the automotive industry. The most important part of the galvanized coating on steel sheets is the zinc coating, which wraps around the material and protects it from corrosion and wear. The galvanized steel, being made up of different layers of zinc and iron alloys, some of which are harder than the iron itself (as shown in the analysis of Figure 11), forms a very resistant coating. This coating is applied to the coils of the sheet and remains throughout the manufacturing process of the components, which represents a problem for some of these processes. Even though galvanized steel can be welded using all the common techniques used in the automotive industry, such as electric arc welding, resistance welding, and laser welding, this coating makes the process more complicated (Staco 2014; Zhang and Senkara 2011; Sejč et al. 2020).

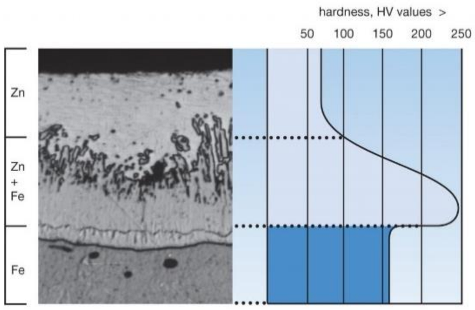


Figure 11 – Diagram of hardness of galvanized coatings (Staco 2014).

Galvanized steel sheets need a much higher welding current since the zinc coating makes the contact resistance lower. During the initial welding cycles, molten zinc is forced out. However, a significant quantity of zinc from the coating can be trapped at the sheet-sheet interface, which contributes to the overall resistance reduction. The presence of zinc coating at the sheet-sheet interface inhibits the correct bonding between the materials, leading to weaker bonding. As Sejč et al. (2020) shows, the best way to avoid the influence of zinc coatings is to apply a hard welding approach (high currents, high clamping forces, and short welding times) that vaporizes and eliminates the coat.

2.1.3.5 Projection shape

The last factor that influences PW is the shape of the projection. The optimal projection shape depends on a number of variables, such as application requirements, material properties, welding parameters, and electrode design. In order to achieve the desired welding quality and efficiency, it is essential to carefully consider each of these factors when choosing the projection shape. (Committee and Metals 1982; Zhang and Senkara 2011)

A projection with a greater area of contact generally results in a more homogenous heat distribution, producing a larger and more uniform weld nugget but requiring more energy. A projection with a narrower point, on the other hand, typically has greater electrical resistance due to its reduced cross-sectional area. This increased resistance generates more heat, which can result in localized overheating if the welding parameters are not precisely controlled. Since the projection's area of contact has a significant impact on electrical resistance and heat generation, it is crucial that, in situations where there are multiple projections, they all have similar shapes and tight tolerances. Otherwise, the current and heat generated will not be uniform between projections, leading to defects(Zhang and Senkara 2011; Weld).

2.2 TMAZ

The thermomechanical affected zone (TMAZ) is the region immediately adjacent to the weld where thermal and mechanical changes occur in the base metal. During welding, the metal's microstructure, and mechanical properties (hardness, strength, and toughness) are altered not only as a result of the rapid heating and cooling, due to the welding process's heat (thermal changes), but also due to mechanical load, such as compressive forces (mechanical changes). The term TMAZ is usually used in Friction Stir Welding and Friction Stir Spot Welding, where TMAZ is commonly used to describe the deformed region outside the stir zone that experiences both moderate frictional heating and plastic deformation due to the tool stirring action (Zolghadr, Akbari, and Asadi 2019). However, it is also used in resistance welding to identify a region that also experiences heat and deformation, albeit in a much different proportion than in friction stir welding (Wu et al. 2017).

In the context of this project, this phenomenon is important given the PW's solid-projection welding type nature. It is expected that, since there is no fusion between the materials and the pressing forces are so high, there will be not only thermal changes but also mechanical changes due to high compression loads. So, in this case, referring to this zone only as a heat-affected zone would be reductive.

2.3 Projection welding electrodes

Resistance welding electrodes are a crucial component of the resistance welding process, which is utilized in a variety of industries to join two or more metal parts together. The electrodes are responsible for delivering high current and pressure to the weld area, thereby producing heat that melts and joins the metals. The main requirement for resistance welding electrodes is high electrical conductivity, which facilitates the efficient transfer of current from the electrode to the workpiece. And good mechanical properties capable of enduring the repeated high-pressure cycles of the welding process without changing their shape or functionality. (Committee and Metals 1982; Zhang and Senkara 2011; Inc. 2021)

The design of the electrode is also crucial to the resistance welding process. Shape, size, and surface polish can all have an impact on the weld's strength and electrode durability. The design of the electrode must be adapted to the particular welding application and materials being welded.

In projection welding, the electrodes are designed to produce strong welds on metal components with projections or embossed surfaces. Typically, these electrodes have a flat surface with a small protrusion that matches the form of the protrusion on the metal component, as shown in Figure 12. The projection makes sure the electric current is focused on the correct location, thereby generating localized heat that melts the metal and creates a robust weld.

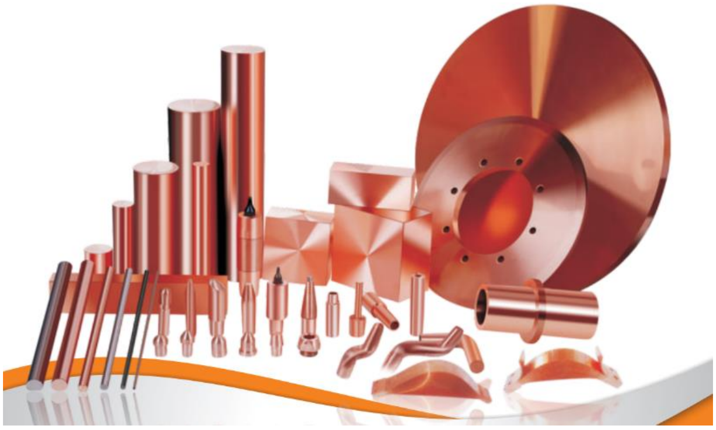


Figure 12 – Projection welding electrode tips and typical materials (METALS).

2.3.1 Materials

To ensure proper and effective welds, it is essential to select the appropriate electrode material. Material selection is influenced by several variables, including the type of material being welded, welding parameters, the production environment, and cost. In general, electrode materials should have high thermal conductivity, high electrical conductivity, good abrasion resistance, and good heat and deformation resistance. For projection welding, the electrodes must be able to withstand the high welding currents while preserving dimension stability and wear resistance.

The use of inappropriate electrode materials can result in issues including electrode adhering, spatter, and excessive wear. This can result in decreased electrode life, increased electrode replacement downtime, and decreased production efficiency. In addition to the size and shape of the projections being welded, the thickness of the materials and the production environment may impact the choice of electrode material. In corrosive environments, corrosion-resistant materials may be necessary.

The material universe is immense, and it must be chosen based on the specific application requirements. However, the commonly used materials for projection welding electrodes include copper, tungsten, molybdenum, and copper alloys of various types. Copper is widely utilized as a result of its high thermal and electrical conductivity, low price, and simplicity of production. Copper-tungsten alloys are also utilized frequently because they combine the abrasion resistance of tungsten with the high conductivity of copper (TWI 2023).

As said, the electrodes are typically made of copper alloys and other materials. In order to standardize these vast possibilities, the Resistance Welder Manufacturers' Association, which is an association respected all around the globe by welders and manufacturers, has divided electrodes materials into groups and classes in order to standardize the electrode materials. The materials are divided into three categories based on their chemical constituents and then into twenty-two classes based on their mechanical properties (Committee and Metals 1982). This standard then evolved into an ISO standard, ISO 5182, that covers the electrode materials for resistance welding. This standard also has three categories and twenty-two classes based on the same criteria (Inc. 2021; Committee and Metals 1982):

- Group A, which consists of copper alloys, is further subdivided into four classes (I, II, III, and IV), with Class I electrodes having the composition closest to that of pure copper. As the class number increases, the hardness and annealing temperature rise while the thermal and electrical conductivities decline.

- Group B, Classes 10, 11, 12, 13, 14, and 15 are the refractory alloys comprised of sintered mixtures of copper and tungsten, etc., intended to provide wear resistance and compressive strength at elevated temperatures. Refractory metals, such as tungsten–copper composites (Classes 10–12), are employed in specialized applications where the high heat, extended weld time, inadequate cooling, and high pressure may cause the rapid deterioration of DSC-base alloys. (Group A).

- Group C, Classes 20, 21, and 22 are powder metallurgy materials composed of copper and aluminium oxide with hardness at high temperatures and distinct physical properties from copper alloys. Not an actual alloy. This group provides an excellent compromise of mechanical properties and electrical conductivity, but at a significantly higher cost.

The most common materials used for PW are classes 2 and 3. Class 1 is not common since Class 2 has a higher mechanical performance with just a slightly lower electrical conductivity. For situations where the requirements are more challenging, classes 10, 11, and 12 are also used (Inc. 2021).

Note that, after analysing the classes and the criteria that led to the sectioning, it is possible to conclude that there is a direct dichotomy between electrical conductivity and hardness. That leads to the question of what criteria we should prioritize. And the answer depends on the application.

2.3.2 Shape

Electrodes for projection welding play a vital role in ensuring a strong and reliable weld between two metal parts. Naturally, shape is also an important feature. It is designed to concentrate heat and pressure at specific locations on the workpiece. Consequently, it influences the overall strength and quality of the weld, as well as the electrodes' own durability and lifespan.

Although there is no standard for the shape due to the infinite types of welds and welding equipment that can be made, The Resistance Welder Manufacturers' Association as some recommendations, such as:

- If the electrode face is large enough to accommodate the projection being welded or the pattern of projections being welded simultaneously, it can be used for projection welding;

- To minimize workpiece marking and indentation, the recommended electrode-face diameter for a single projection weld is typically two or more times the projection's diameter;

- In multiple-projection welding, the electrode face should be large enough to extend approximately one projection's diameter beyond the projection pattern's boundaries.

The electrode’s flatness, settlement, and surface finishing or roughness are also crucial. The flatness and the settlement, combined with the machine-construction tolerances, are crucial to ensuring that the welding process does not introduce undesirable geometrical distortions that lead to an uneven collapse of the projections, which can be critical in performance.

Concerning the roughness or finishing, it's important that the surface in contact with the materials being welded has a fine surface finish to reduce the contact resistance. The temperature should rise between the projection and the second material, not between the electrodes and the materials being welded (Hamedi and Atashparva 2017).

Finally, another important factor regarding the shape is that it should have a water-cooling circuit if possible. Which would be a major gain to improve the durability and extend the lifespan. There are some works in the literature that have studied the optimal dimensions and flow for the water cooling. For example, Lai et al. (2009) has arrived at a specific combination of geometrical dimensions that optimizes the cooling effect.

2.3.3 Wear

In the automotive industry, PW electrodes are indispensable for welding fasteners to sheet metal. During the procedure of welding, these electrodes are used intensively and continuously, resulting in various forms of wear over time. Essentially, projection welding electrodes can be subjected to two types of wear: mechanical deformation of the electrode surface and metallurgical changes. These main types can be divided into electrode face wear, cracking, shank wear and deformation.

Electrode face wear is a type of wear that is a symbiosis between mechanical wear and corrosion that develops as a result of constant contact between the electrode and the workpiece's surface at high temperatures.

During the welding process, the galvanized coatings (Aluminium and Zinc) and the Fe of the fasteners will react with the electrode surface, originating the formation of brittle brass alloys on the top of the electrodes that will stick and fracture, leading to pitting and progressive erosion. Pitting may also be a result of the electrical arc that can be generated during the weld. Moreover, the presence of oxygen during this high temperature process also leads to the oxidation of the copper. This presence of alloys, pitting, and oxidized copper increases the electrical and thermal conductivity of the electrode’s face (Enrique et al. 2019).

Shank wear is a form of wear that can happen on welding electrodes for fastener projections. During the welding procedure, friction between the electrode shank and electrode holder causes this deterioration. This friction can wear down the shank over time, resulting in misaligned electrodes and diminished welding quality. When the electrode is misaligned, it might not have adequate contact with the fastener, resulting in an uneven distribution of current and force, leading to poor nugget formation or incomplete welds. Therefore, it is essential to inspect and replace (if necessary) electrode holders on a regular basis to prevent shank erosion and ensure optimal welding performance (Association 1942).

Cracking is another form of deterioration that can occur in projection welding electrodes. The electrode material may develop microcracks as a result of repeated heating and cooling cycles during the welding process. Eventually, these microcracks can propagate and contribute to larger cracks in the electrode. Which not only reduces the electrode's ability to conduct electricity, which can damage the weld quality, but also can lead to total failure of the electrode. Water cooling systems are the best way to prevent this phenomenon (Association 1942; Committee and Metals 1982).

Another type of degradation that may take place on projection welding electrodes is deformation. During the process of projection welding, a great deal of force is applied to the electrode, and this can cause it to deform or distort. This deformation can occur in various electrode components, including the tip and shank. When the electrode deforms, it could fail to establish proper contact with the fastener, resulting in subpar or incomplete welds. To mitigate deformation and guarantee optimal welding performance, it is essential to employ electrodes developed to withstand the high forces generated by projection welding (Association 1942; Zhang and Senkara 2011)

2.4 Taguchi's method

Due to its basic principle, cost-effectiveness, and other attributes, projection welding is widely used in the assembly of automobile bodies and other processing sheets/fasteners. However, even in processes where PW is simple to implement, the factors that determine the quality of the weld strongly influence one another, making it challenging to achieve satisfactory welding quality. Setting the necessary conditions to achieve the desired weld quality by trial and error is an inefficient task. Consequently, it is necessary to determine the optimal conditions for producing the desired weld quality using a welding process model that conveys the weld quality with the minimum number of experiments.

Dr. Genichi Taguchi developed the Statistical Taguchi Method to minimize the impact of uncontrollable factors on product or process performance by emphasizing robust design principles. Utilizing statistical methods, design-of-experiments (DoE), and optimization principles, it improves quality and reduces cost. The method seeks to improve product dependability and customer contentment by systematically analysing influential factors and their levels (Peace 1993).

When the number of process parameters increases, multiple experiments must be conducted. Taguchi's method employs a unique design of an orthogonal array to investigate the entire process parameter windows investigated, requiring only a small quantity of experiments. Using orthogonal arrays to design experiments enables designers to investigate the influence of multiple controllable factors on the mean and variation of quality characteristics in a timely and cost-effective manner.

In welding applications where quality and dependability are of the utmost importance, the Statistical Taguchi Method offers substantial advantages. It enables engineers to produce high-quality welds while minimizing defects, distortions, power consumption, and cost while increasing the integrity, strength, and durability by optimizing welding parameters (Phadke 1989).

The fundamental stages of the Taguchi Statistical Method include:

- Define the problem or objective clearly, such as improving weld quality, reducing defects, or increasing strength.
- Determine the controllable factors (parameters) that substantially influence the output (response) and their respective levels for parameter design.
- Signal-to-Noise (S/N) Ratio Analysis: Employ S/N ratios to evaluate the quality attributes and optimize the performance. And apply statistical techniques, such as analysis of variance (ANOVA) and regression analysis, to experimental data.
- Confirmation Test to Validate the Optimized Solution through Additional Experiments and Evaluate the Resulting Improvement

Signal-to-Noise (S/N) Ratio Analysis is a measure of robustness used in Taguchi designs to identify control factors that reduce variability in a product or process by mitigating the effects of uncontrollable factors (noise factors). Noise factors cannot be regulated during production or product use, but they can be regulated during testing. In a Taguchi-designed experiment, noise factors are manipulated to induce variation, and the results are used to determine the optimal control factor settings that make a process or product robust, or resistant to variation caused by noise factors. Greater signal-to-noise ratio (S/N) values indicate control factor parameters that mitigate the effects of noise factors. In welding, such values are the set of parameters that give the best welding (Minitab 2023b).

ANOVA analyses evaluate the significance/contribution of one or more factors by comparing the means of the response variable at the various factor levels. In welding, it means which parameters are more significant and consequently have more impact on the weld quality (Minitab 2023a).

3 Problem proposed

Before moving forward with the detailed presentation of the problem proposed, it is important to mention that the goal for Gestamp Cerveira is to select a new material for the PW electrodes and eventually standardize for the nineteen PW machines in Gestamp Cerveira. However, since the machines produce different parts with different specifications and details and the time for the project is short, the company initially focused on a specific part made on a specific machine. Then, based on the conclusions obtained, standardize the other welding equipments if possible. Taking this into consideration, the problem will now be presented.

3.1 Problem presentation

Following a prior study on the company by Eng.a Mariana Souto, Gestamp Cerveira's project emerged. In her study, where the main goal was to optimize the welding parameters, she identified an opportunity regarding the electrode materials. When analysing the machine setup, she realized that the electrode has a significantly lower electrical conductivity than the part that supports it, which offers a resistance on the circuit. Moreover, an electrode with a better conductor would be more efficient. So, following her study, Gestamp proposed this project, whose objective is to study new electrode materials for a welding machine that produces a component made to support a car suspension. And then, eventually standardize for all the welding machines.

3.2 Component and welding equipment investigated

3.2.1 Description

Back in 2017, Gestamp Cerveira signed a contract with one of his clients to make the "*Support Suspension "*. This component emerged with the launch of 3 new automotive models' fleets, where this part is assembled the component consists of two symmetrical references (references 1 and 2, Figure 13) produced by a dedicated pedestal welding machine. Each one is composed of a piece of stamped steel, where two bolts are welded. Its function, as the name implies, is to support the suspension of the cars. In the following Figures 13 and 14, it is possible to see the two references and the zone where the part is assembled on the car structure.

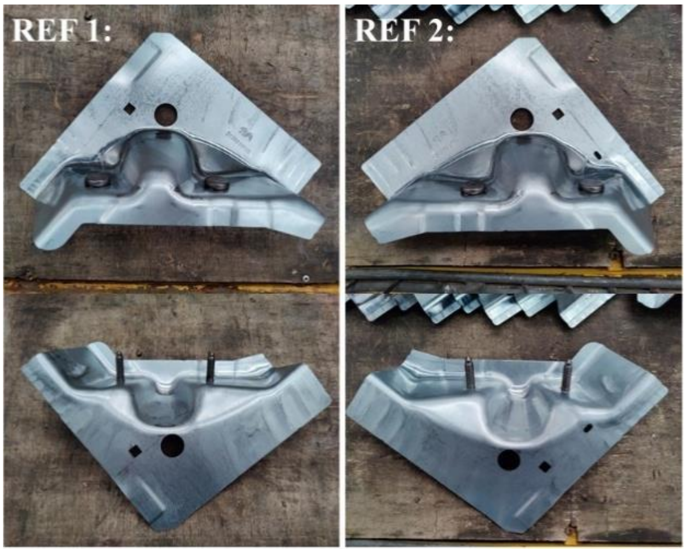


Figure 13 – References produced on the pedestal machine under study.

Figure 14 – Zone and cars where the part is assembled on the car structure.

3.2.2 Manufacturing process

Starting with the stamped steel part, this component is made of FB60 steel (EN HDT 560F), whose chemical composition is represented on Table 1. It's manufactured internally using presses, and its manufacturing process can be described as follows: the raw material arrives at the company in coils with the specifications shown on Table 2, then it goes to a press where the stamping tool is already assembled (matrix + punch) and here it undergoes a sequence of punches as shown in Figure 15 until it arrives at the final shape.

Table 1 – Chemical composition pf the raw material of the plate (Gestamp Cerveira 2023b).

Chemical Composition [% mass]							
C eq.	**C max.**	**Mn max.**	**Si max.**	**P max.**	**S max.**	**Al max.**	**Nb max.**
0.440	0.180	1.600	0.450	0.025	0.010	0.015	0.030
Ti max.	**V max.**	**Cr max.**	**Mo max.**	**B max.**	**N max.**	**Ti + Nb max.**	**Cr + Mo max.**
0.030	0.060	0.100	0.040	0.005	0.008	0.050	0.100

Table 2 – Coil Characteristics (Gestamp Cerveira 2023b).

Coil Characteristics			
Thickness	**Width**	**Coating**	**Coating Thickness**
2 mm	690 mm	Galvanized	10 µm / 10 µm

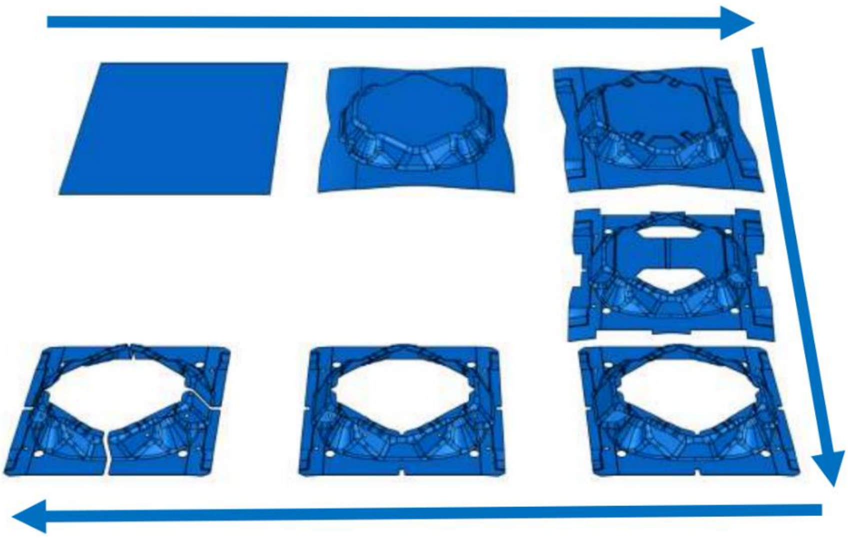


Figure 15 – Schematic representation of the tamping sequence of the component under study (Gestamp Cerveira 2023b).

The second and last component are the bolts for projection welding. These M12 bolts are bought from an external supplier, PECOL Automotive, which is a fastener manufacturing company. The fastener’s chemical composition, and some mechanical properties are presented on Table 3. It is quenched and tempered class 10.9 and has no surface treatment. The part and its geometrical tolerances are represented in Figure 16. As it's possible to see, the bumps on the base of the bolt head are what penetrates the steel sheet, concentrate the current, and promote the welding.

Table 3 – Chemical composition of the bolt welded in the process under study (Gestamp Cerveira 2023b).

Chemical Composition [% mass]							**Mechanical Properties**	
C max.	**Mn max.**	**Si max.**	**P max.**	**S max.**	**Al max.**	**B max.**	**Hardness**	**Yield Strength**
0.3600	0.7150	0.0760	0.0040	0.0040	0.0320	0.0040	37–38 HRC	1139 – 1232 MPa

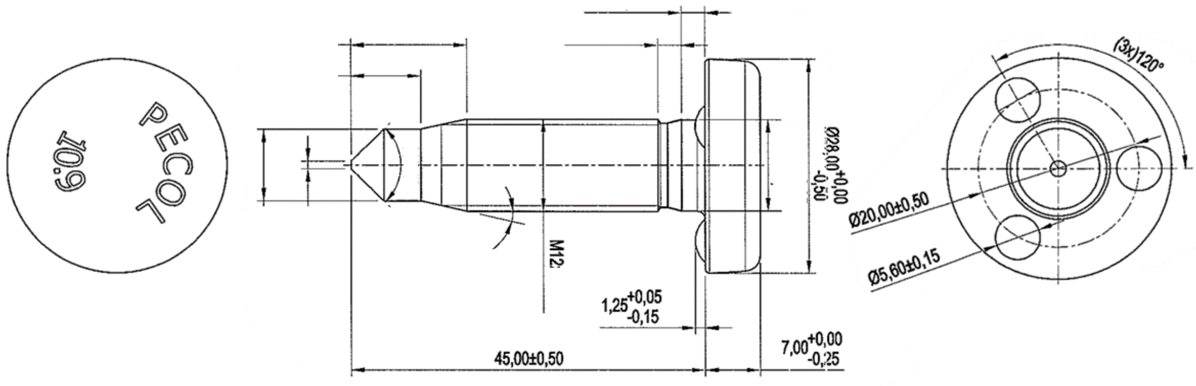


Figure 16 – Representation of the PECOL Automotive bolt welded in the process under study (Gestamp Cerveira 2023b).

The pedestal welding machine is presented in Figure 17 and in Figure 18 in more detail. As seen in Figure 18, the machine is composed of several parts. Note that the top electrodes are grip-fixed to the electrode holders, whereas the bottom electrodes are nut-fixed. And that, the current is transmitted to the bottom tool through the base, and from the top to the top electrode's holders.

In this machine, there are three separate systems: the water-cooling system, the pneumatic system, and the electrical system. The water circulates through components 1, 2, and 3 in order to prevent overheating. The pneumatic system is responsible for applying the welding force. And the electrical system is responsible for the current supplied for the welding itself and the other control and security systems.

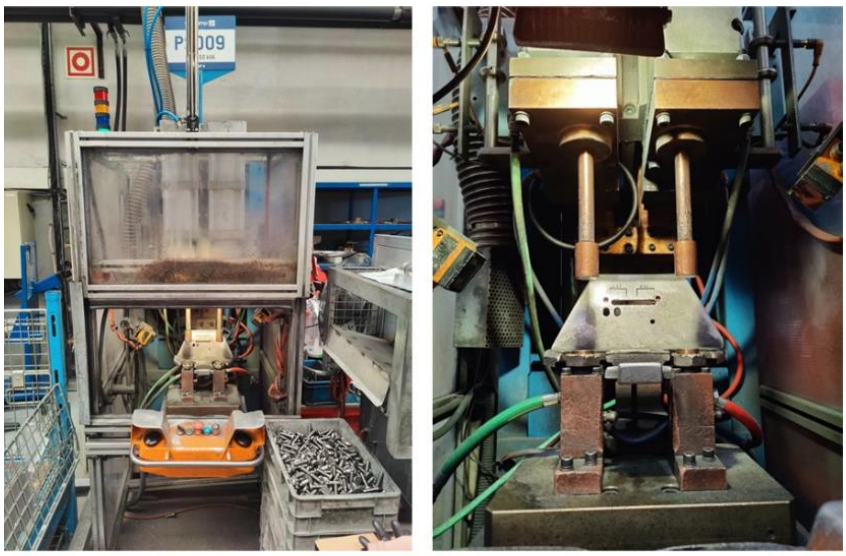
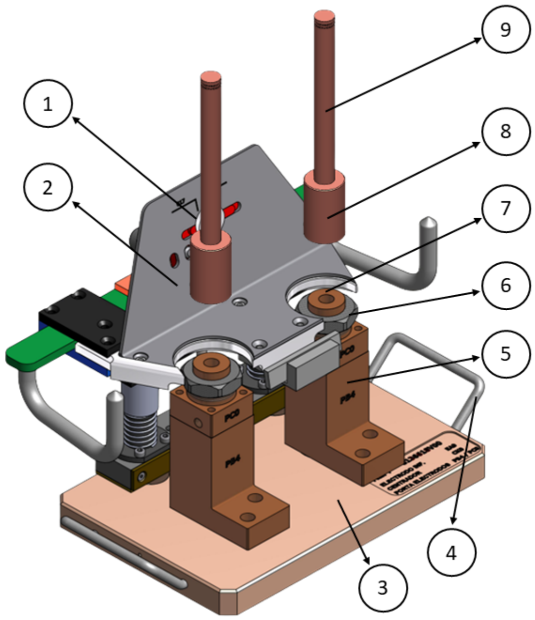


Figure 17 – Overview of the pedestal welding machine.



Number	Name
1	Anti-error
2	Backrest of the piece
3	Base with expulsion
4	Handles
5	Electrode holder
6	Lower electrode fixing nut
7	Lower electrode
8	Top electrode
9	Spear

Figure 18 – Detailed schematic view of the pedestal welding machine and its individual components.

Subsequently, upon providing a comprehensive description of the components and the welding machine, the next step entails the actual welding of the parts. To elucidate the welding stages effectively, it is recommended to adhere to the sequential arrangement depicted in Figure 19, in conjunction with the subsequent descriptive account:

i. As expected, at the start, the machine is empty and on standby.

ii. Then, the operator starts by mounting the parts on the machine.

iii. After that, the operator presses the two buttons to proceed with the welding, and if the safety systems do not detect anomalies, the protective door closes, and the pneumatic system descends the top electrode with the predetermined force. Once the electrode is fully down and the welding force is achieved, the electric system discharges the current, and the weld occurs. The first descent welded the left bolt (*bolt A*).

iv. To weld the right bolt (*bolt B*), step iii) is repeated for the other side.

v. Lastly, after a determined time (cooling time plus pressing time), the top electrodes ascend, and the door opens for the worker to take the finalized component out.

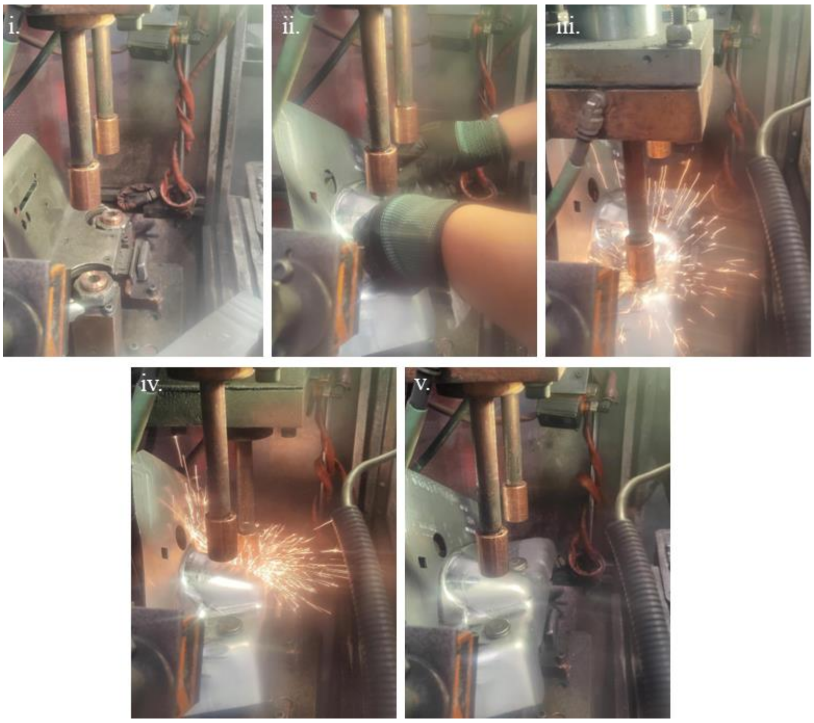


Figure 19 – Welding stages in the pedestal machine.

3.2.3 Application and requirements

As already mentioned, the component's application, as the designation says, is to support the car's suspension. Naturally, the part not only has to support significant loads but also have tight geometrical tolerances in order to correctly assemble on the car's structure.

Regarding the geometric tolerances, the company has developed a quality model (Figure 20) based on the client's requirements and the normative IATF, which is mandatory. The geometric requirements are so defined. Since these tolerances will not be the most important in our study, they will not be specified, but they will always be fulfilled.

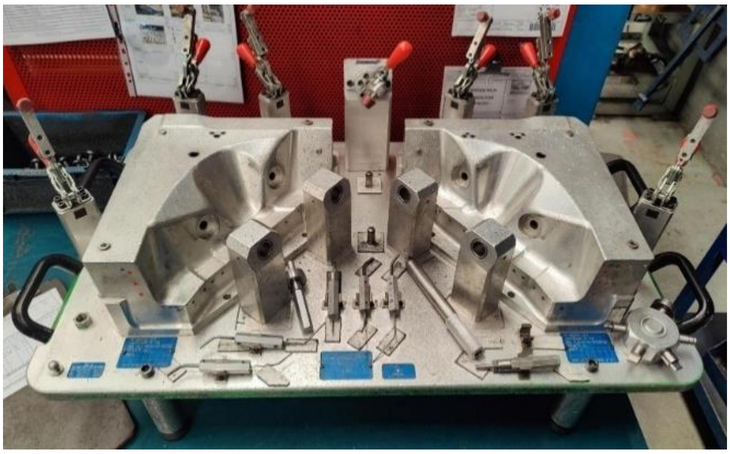


Figure 20 – Quality model of the part under investigation.

The mechanical requirements are harder to define since the component is subjected to a variety of loads. Fortunately, the categorization and definition of the mechanical requirements are done by the client, so from the company side, the only requirements that should be followed are already pre-defined. For this component, the mechanical requirements that should be accomplished are:

- Rupture force greater than 15 KN for a tensile rupture test following the client normative.
- Until 15 KN of force is applied, at least two weld nuggets must not fail.

The tensile rupture test is done using a HOYTOM press machine (Figure 21), using a tube and a punch (Figure 22) with the characteristics specified in the customer standard. In Figure X, it is possible to see the before and after the test and the load measurement.

Figure 21 – Rupture test HOYTOM press machine.

Figure 22 – Punch and tube for the rupture test of the component.

4 Solution proposal

After finishing the problem presentation and the integration in the company, it was time to propose, test, and validate solutions. For that, it was first necessary to not only deepen the knowledge about projection welding and all the nuances involved but also, and most importantly, spend time on the factory floor. That time was a combination of three things: observation, analysis, and talks with the working personnel. It was important because it enabled an understanding on how the machine works, its strengths and limitations, the opportunities for future improvements, and take some notes from the people that work on and maintain the equipment.

Considering all this knowledge acquired on the field and combining it with the literature, experience, and willingness for improvement, it was necessary to start pursuing the path to a possible solution. The approach used to achieve this is what is described in the present chapter.

4.1 Manufacturing variables and details

Since the welding under study is crucially dependent on its manufacturing details, parameters, and setup, as seen in Chapter 2. Time on the factory floor is crucial to characterizing all the details involved in the manufacturing process. Otherwise, the chance of the solution failing is almost guaranteed, given the nuances involved. So, this topic was dedicated to characterizing all the important variables to take into consideration during the study.

4.1.1 Electrode's materials and service life

The electrode´s material is the same for the top and bottom electrodes. And the material is AMPCOLOY 95, whose properties are represented in Table 4. Note that the selection of this material is based on the manufacturers' experience and general guidelines written in books and scientific articles.

Since the beginning, the company has assumed, as it is customary in the automotive manufacturing sector, that this material is the best option for PW because it has relatively good mechanical properties without considerably compromising electrical conductivity. The study made for this project is the first time the company has had the chance to investigate the process in detail and change the material to optimize the process.

Table 4 – AMPCO 95's chemical and mechanical properties (METAL 2023).

	AMPCOLOY 95
Chemical Composition [% mass]	97,5Cu 0,5Be 2Co+Ni
Hardness Rockwell / Brinell	100 / 240
Yield Strength [MPa]	537
Elongation [%]	17
Electrical Conductivity [% IACS]	45
Thermal Conductivity [W/mK]	218
Young Modulos [GPa]	117
Max. Working Temperature [ºC]	450

The electrode's service life is as follows:

- The company buys a bar of AMPCOLOY 95 with a diameter of 30 mm and uses a CNC lathe to make both the top and bottom electrodes.
- They are assembled in the machine and do 2500 welds. The selection was based on a visual evaluation of the electrode's wear and experience.
- Then the electrodes return to the CNC lathe and are passed on at 0.02mm on the face that is worn and goes back to the welding machine. This step is repeated until the electrodes do not reach the minimal length threshold.
- If the electrode cannot be machined again, the material is scrapped.

4.1.2 Geometry of the connecting bolts

The geometry and dimensions of the bolt bumps were found to vary. The bump height is relatively constant, but the shape and concentricity of the bumps vary considerably, as shown in Figure 23. Some bumps are flattened more than others (contact area variability), and the bolt head centring is not consistent. Some bolts have the head misaligned with the stud (Figure 23 a)).

The shape highly influences contact resistance. Flattened bumps (higher contact area) imply lower contact resistance, leading to lower heat generation, while non-deformed bumps lead to the opposite. Concentricity interferes with the loads and current distribution, leading to different heat generation and pressure forces in each projection. Consequently, as seen in Chapter 2.1.3.5, different weld qualities. These phenomena cause a lot of variability, which complicates the weld quality and its consistency.

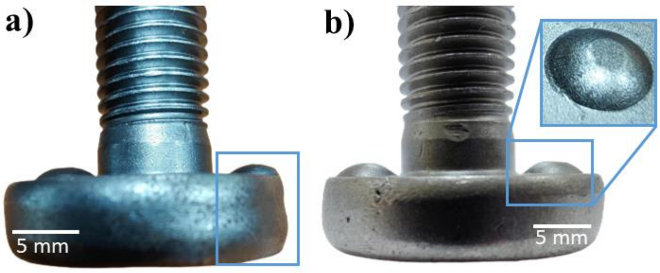


Figure 23 – a) bolt's centring defect; b) bolt's bump flatten defect.

4.1.3 Flatness problems

Due to the stamping process itself, there are flatness problems around the zone where the bolt bumps settle, and that impacts the weld quality. This phenomenon is illustrated in Figure 24 a), where the marks were obtained by pressing the bolt against the steel plate with welding force. Note that, as is possible to see, there are significant differences in circle dimensions that consequently influence the power distribution between projections. Bigger marks mean that the bumps were positioned at higher points (a mount) and the little ones at lower points (a valley).

This experiment was also important to define the critical position of the bolt, which leads to greater differences in the area of contact between projections. As is possible to see in Figure 24 a), the bolt position that leads to the projection's marks 1, 2, and 3 is the worst combination. Such is also confirmed after a weld in that position. Figure 24 b) shows that the projection corresponding to position 1 is clearly above a valley (a higher gap between the fastener and the plate). The company has been successfully making efforts to minimize this defect. One simple approach used to control this problem was to overdimention the welding parameters.

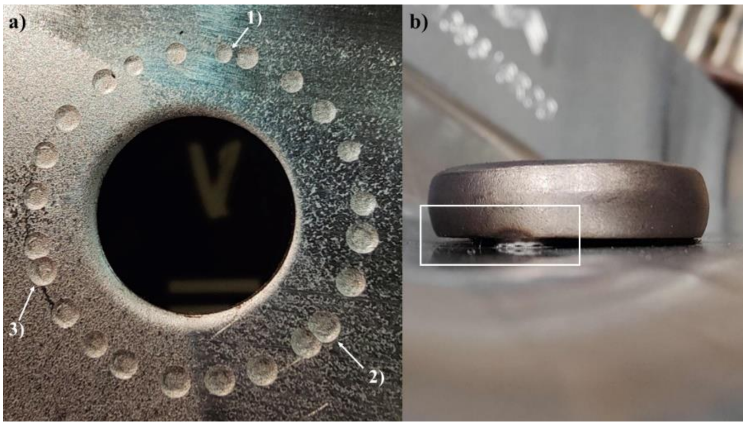


Figure 24 – a) Plate marks resulted from the pressing of the bolt in different positions with welding force; b) Bolt welded in the critical position,

This defect, combined with the unpredictable position in which the bumps can be placed, in the welding setup prior to the process, the electrode's misalignment, and the bolt's bumps dimensions and shapes, generates a variability that highly influences the weld quality and consistency.

If a projection is placed above a valley, similar to case a), represented in Figure 25 a), when it properly makes contact (physical contact in which the contact resistance is small enough to allow the current to pass through) with the plate surface after the other projections collapse, not only will there not be sufficient current to promote a good weld, since the current escape by the other bumps (resistance on the other collapsed projection is significantly lower), but there will also be less time to melt since the welding time is already underway.

If a projection is placed in a mount, like in case b), represented in Figure 25, two things can occur. Since it is subject to more pressing pressure, it will deform and increase the contact area, reducing the electrical resistance and the heat generation, and consequently, the maximum temperature achieved will be lower. If the pressure is not enough to promote deformation, as the majority of the current will pass through that projection, the heat generated will be excessive and lead to an unpredictable collapse and expulsion, which is a defect that consists of the expulsion of melted material. This last case is not as critical and common as case 1 (WELD 2020).

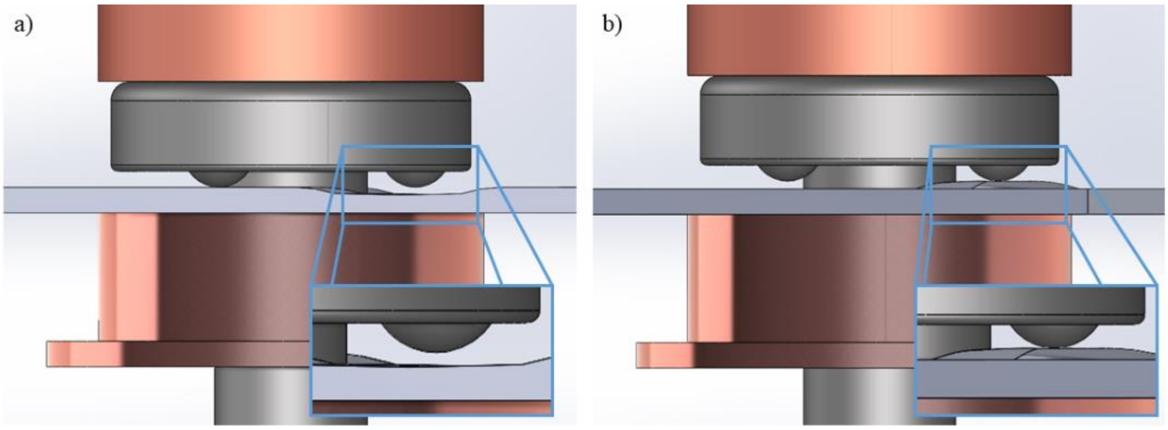


Figure 25 – Different critical welding scenarios arise due to flatness defects. a) Valley; b) Mount.

Fortunately, due to symmetry, these defects appear in both references in a symmetrical way. This enables the study to define the electrode's material and parameters by considering only the critical position for one reference and then generalizing to the other (the left electrode of reference 1 will be the right electrode of reference 2, and vice-versa).

4.1.4 Electrode's misalignment and water-cooling

The top electrodes are not centred with the fasteners due to misalignments on the welding equipment, as seen in Figure 26. This leads to two major problems. It presses the bolts unevenly, which causes differences in the bumps to collapse. And it does not cover all the bumps on the bolt, which unevenly distribute the current through the bumps. Moreover, since the welding force is applied to a smaller area than expected, it will increase the wear rate.

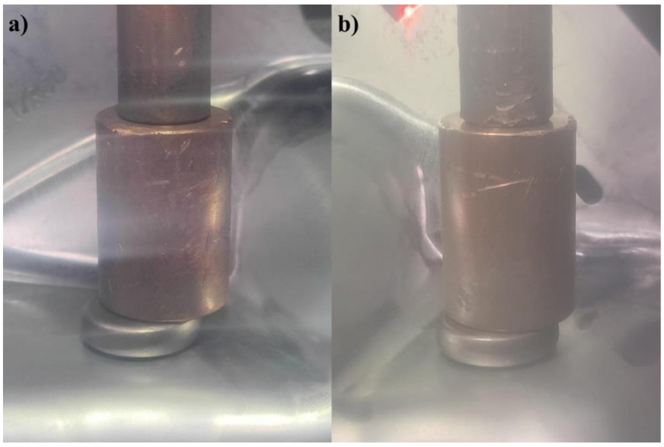


Figure 26 – Electrode misalignment in the pedestal welding machine.

Regarding the water cooling, the top and bottom electrodes don't have direct water cooling, only the electrode holders do. This also contributes to the increase of the wear rate.

4.1.5 Bolt's engravings

After observing several components being produced, it was noticed that the engraving on the top of the bolt head (PECOL 10.9) generate heat given that these entrap air during the process, which increases the electrical resistance. This may seem like a small detail, but it is energy that is dissipated without need and heat that wears the top electrode. The reddish zones between the top electrode and the weld in Figure 27 demonstrate this phenomenon occurring. This finding was noted not only by Gestamp for future iterations and improvements, but it was also shared with PECOL due to the economical and sustainable benefits that this small change can originate.

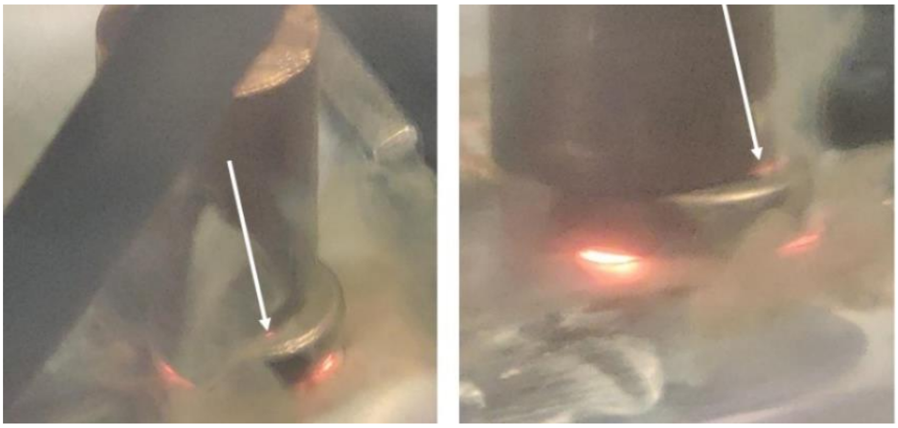


Figure 27 – Hot zones resulted from the bolt's engravings.

4.1.6 Welding parameters

Currently, the parameters that the company has defined are represented in Table 5. These parameters were defined on an experience-based knowledge, without a systematic investigation.

Table 5 – Welding parameters in use in the pedestal welding machine.

	Bolt A	Bolt B
Welding Current [kA]	20	20
Welding Pressure Force [kN]	11	11
Welding Time [ms]	360	360
Cooling Time [ms]	600	600

4.1.7 Welding type

Since the welding in PW could be embossed-projection welding (fusion) or solid-projection welding (forged and diffusion bonding), and the parameters such as force highly influence the weld, it is crucial to characterize the weld in order to propose improvements and solutions. This characterization was based on the analysis of both weld macrographs and weld nuggets that had failed. Figure 28 represents a case where the weld nugget failed even though the mechanical requirements were verified. Analysing this failure, it is possible to see ductile failure (greater roughness) primarily on the outside (nugget b) but also, in some cases, on the inside (nugget a) and, brittle failure (little roughness, visible on nugget b), that appears mostly on the inside. Such finding leads to the suspicion that this weld type is an embossed-projection welding (ductile failure) on the outside diameter and solid-projection welding (brittle failure) on the inner diameter area.

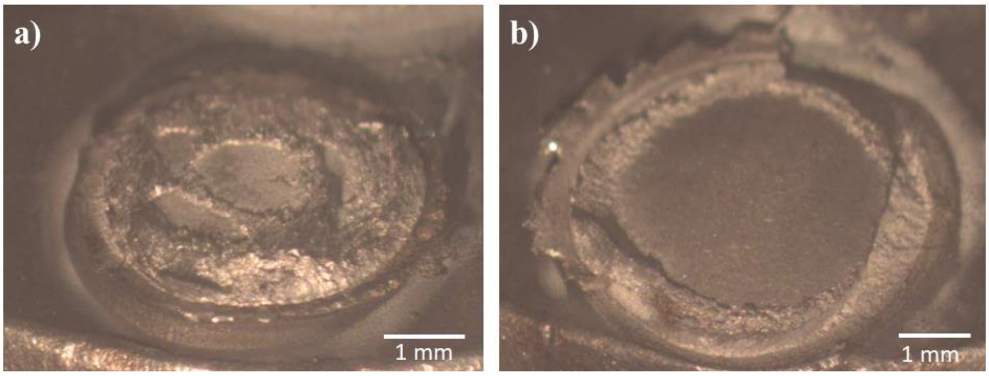


Figure 28 – Two weld nugget macrographs that have failed.

The previous analyses were based only on weld nuggets that failed. For that reason, macrographs of weld nuggets that failed (Figure 29 a)) and those that did not (Figure 29 b)) were taken to corroborate the conclusion. As is possible to see from the micrographs represented in Figure 29, in fact, there is fusion mainly between the materials on the outside (zone 1) and none/low in the interior (zone 2). Zone 2, where the interface between the materials is obvious (diffusion bonding), causes brittle failure, this type of bond is weaker, as is possible to see in Figure 29 a), this weaker bonding was not capable of rip off material from the steel plate. While Zone 1, where the interface is dissipated (majorly on the outside) due to fusion, causes ductile failure which is a much stronger bonding type. Such is visible in figure W a) zone 1 where steel was ripped off from the plate. (Enrique et al. 2019)

Given that the characterization, through the micrographs, support the first analysis and hypothesis, the weld was found to be a mixture of both welding types.

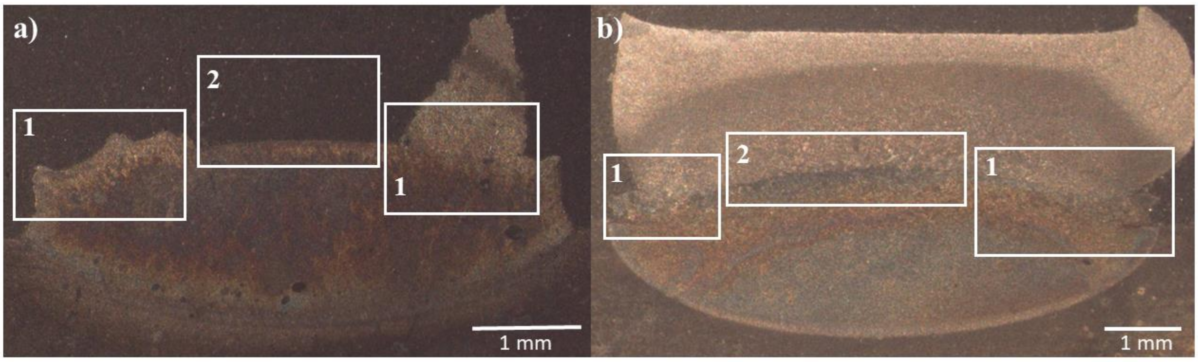


Figure 29 – Two weld nugget macrographs: a) a nugget that failed, b) a nugget that did not fail;

During this analysis, other interesting conclusion emerged:

- It appears that the greater the amount of forged welding, the weaker the welding becomes. In order to avoid this, welding parameters that ensure fusion, leading to stronger welds, should be defined. Such tests were conducted while defining the welding parameters (see Chapter 4.4.1.2).
- Higher projection collapse (severe local plastic deformation due to material softening and pressure forces) rates (nugget b) originate bigger nuggets with a prevalence of solid projection welding type (forge).
- Lower projection collapse rates (nugget a) lead to smaller nuggets with a predominance of embossed projection welding (fusion).
- The fusion present primarily on the outside diameter indicates that the weld occurs from the outside to the inside, which is a result of high welding forces and low welding time (Chapter 2.1.3.2).

The type has been introduced. However, given the direct influence of the welding type on the quality and strength of the weld, it is crucial to understand the most suitable welding approach for the case at hand. Nevertheless, a thorough examination and discussion of this matter will be presented in forthcoming chapters.

4.2 Wear of the electrode

4.2.1 Motivation and objective

During the time on the factory floor, two questions started to emerge, one resulting from the literature and the other from the observation of the production. The first, as already mentioned in Chapter 2.3.1 about the materials, is about the dichotomy between electrical conductivity and hardness and which one should be prioritized for the material of the electrodes. This decision is important since electrical conductivity directly impacts power consumption and is the main parameter regarding the minimization of power dissipation. On the other hand, the hardness is directly related to the electrode's durability.

An additional concern emerged following a discussion with the maintenance and quality departments. Notably, their response regarding the material selection and durability of the electrodes proved intriguing. It was revealed that both decisions were primarily guided by subjective evidence and conventional wisdom, with the practice of visually assessing the wear of the electrodes as the sole basis for replacement lacking substantial empirical or experimental support. This revelation has sparked a keen interest in evaluating, analysing, and comprehending the phenomenon of electrode wear.

Furthermore, while researching materials for PW electrodes and their impact on the durability, an article by Enrique et al. (2019) stated, that despite PW being a manufacturing process widely used all around the world and that crosses several areas of engineering, there have not yet been significant studies made related to the impact of the electrodes wear on the welding quality. Due to this lack of knowledge, manufacturers (such as GESTAMP) draw a parallel with spot welding and take it as common knowledge that the wear is detrimental to the quality of the weld. This, as Enrique et al. (2019) concluded in their study, could not be the case for projection welding. The authors arrived at experimental evidence that suggests that electrode wear promotes the formation of a thermal capsule around the welding zone, which promotes better fusion and diffusion bonding with almost the same power consumption.

Motivated by this question and the mentioned investigation, the next step was to make an investigation about on the impact of electrode wear on welding quality.

In this study, the objective is to follow and analyse the evolution of some parameters such as power consumption, load at rupture, visual appearance, type of rupture, weld nugget, and TMAZ with electrode wear. After this investigation, it was expected that it will be possible to draw conclusions regarding the real impact of wear on the welding quality and, from that, understand which property, electrical conductivity, or hardness, should be prioritized when assessing and choosing alternative materials for electrodes.

4.2.2 Methodology

The methodology followed in this study naturally had to be established in such a manner that would cover all the objectives of the work. The methodology followed and respected the following points and is summarized in Table 6:

- For this study, the electrode's life cycle was increased from the used 2500 to a tentative number of 5000 cycles.
- The electrode's life cycle was divided into five stages for experimental run.
- A rupture test was done, according to the client norms for the stages corresponding to 1, 1250, 2500, 3750, and 5000 electrode performed cycles of welding. For scientific purposes, three tests were performed for each stage.
- A power consumption measurement was done for each stage. For statistical reasons during 100 welds. For the first stage, during the first 100 welds. For the next three stages, it was measured at fifty before and fifty after the set mark. And then, for the last one, 100 before the 5000 welds.
- A weld's micrography and an electrode's macrography were done only for the 0 welds, 2500 welds, and 5000 welds.
- From 0 to 2500 it was verified if the metallic part satisfied the requirements (rupture test and geometry tolerances on the quality model). From 2500 onward, the internal quality control procedures were tightened to guarantee that the metal parts still fulfilled the client's requirements.
- Since as seen in Chapter 3.2.1 the welding machine produces two symmetrical references, all the tests were performed on the same reference, *reference 1* to guarantee the same conditions and avoid variability.
- For the parts tested, the fasteners were positioned in a manner to guarantee that they followed a common procedure to avoid variability in the setup.
- The water-cooling flow was kept above 15, which is the value defined as the minimal acceptable (around 29 l/min all study).

Table 6 – Methodology followed for the electrode's wear study.

Nº of Welds	Rupture Test	Power Consumption	Weld's Macrography	Electrode's Macrography
1/2/3/4	✓	✓	✓	✓
1250/1251/1252	✓	✓	×	×
2500/2051/2502/2503	✓	✓	✓	✓
3750/3751/3752	✓	✓	×	×
5000/5001/5002/5003	✓	✓	✓	✓

For this study, there was an important detail that had to be considered. As explained in Chapter 4.1.3, the flatness on the surface where the projections settle is not perfect, which can influence the weld quality. Considering this, it is important to control the position of the projections in this study, so not only to avoid variabilities, but also to study the worst scenario, guaranteeing the reliability of the study.

Despite the awareness of this flatness issue, the only way to effectively quantify it is using 3D scanning, which was a resource that was not available for the present work. For that reason, an optical evaluation of the surface was performed to identify critical locations where the flatness defects were more severe. It was observed that the left surface, where *bolt A* sets, had good flatness. So, in this case, the identification of critical points for *bolt A* was not critical. Even so, to avoid variability in the setup, *bolt A*'s position was defined. On the contrary, on the right side (*bolt B*), there was a higher degree of flatness defects. For that reason, in this case, the bolt and consequently its bumps were positioned carefully and in a position that corresponds to the worst scenario. That means bumps in valleys and others in mounts that lead to different areas of contact. Such position was already mentioned in Chapter 4.1.3 and can be seen in Figure 24 a).

All the components for testing were marked, prior to the welding, to correctly position the fastener's projections in the most critical position and to avoid variability. This stage is represented in Figure 30.

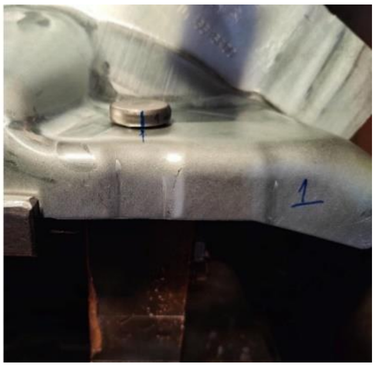


Figure 30 – The representation of the bolts painted and positioned in the critical position.

After all the welds had been made, it was necessary to produce the samples for macrographic analysis. These samples were made with the help of the metallographic laboratory following these steps:

I. A cut was performed through the most critical projection and the center of the bolt on the cutting machine, represented in Figure 31 a).
II. The samples were then embedded in epoxy and cured using the machine represented in Figure 31 b).
III. Perform a 3-stage grinding and polishing procedure was done using the machine represented in Figure 31 c).
IV. A chemical etching using Nital 5% to evidence the different zones and the grains.

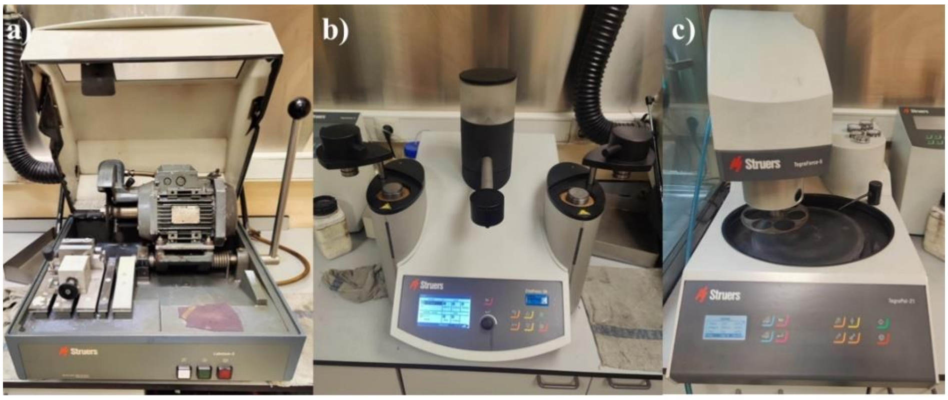


Figure 31 – Different stages to obtain the weld samples for macrographic analysis: a) cutting; b) sampling; c) polishing.

4.2.3 Experimental results and discussion

4.2.3.1 Rupture test

Starting with the destructive test performed on the HOYTOM press machine, the results are shown in Table 7 and in Figure 32. Analysing these results, it is possible to draw the following observations:

- For *bolt A*, which is where the flatness problem does not have significant impact, the results are consistent and considerably above the 15 kN requirement for the mechanical performance. Such consistency suggests that the geometrical defects of the bolts (Chapter 4.1.2) did not cause significant variability. Considering that in this case, the variability associated with flatness defects could be despised, it was stated that the bolts geometrical defects themselves did not have a greater impact on the weld quality.

- For *bolt B*, it is possible to see that there was much more variability in the rupture loads. Such phenomena occurred because the variability associated with the projection positioned in the critical position was kept in the critical position, combined with the variability resulting from the bolt geometrical defects, reduce the conditions for a good weld. In short, both variabilities and defects combined resulted in inconsistency in the weld quality.

- For 5000 cycles, the required performance continued to be satisfied. Even in the worst scenario (*bolt B*), the values continue to be above the requirements.

Table 7 – Rupture test results of the Electrode´s Wear Study.

Rupture Load [kN]	Bolt A				Bolt B			
Nº of Welds	Sample 1	Sample 2	Sample 3	Average	Sample 1	Sample 2	Sample 3	Average
1	22.87	19.61	23.7	**22.06**	17.66	22.95	22.89	**21.17**
1250	23.98	24.65	24.82	**24.48**	14.71	15.08	23.77	**17.85**
2500	24.16	22.97	24.38	**23.84**	25.21	25.47	25.40	**25.36**
3750	24.98	22.64	25.66	**24.43**	15.51	19.41	18.02	**17.65**
5000	25.66	26.5	25.88	**26.01**	20.72	24.79	25.02	**23.51**

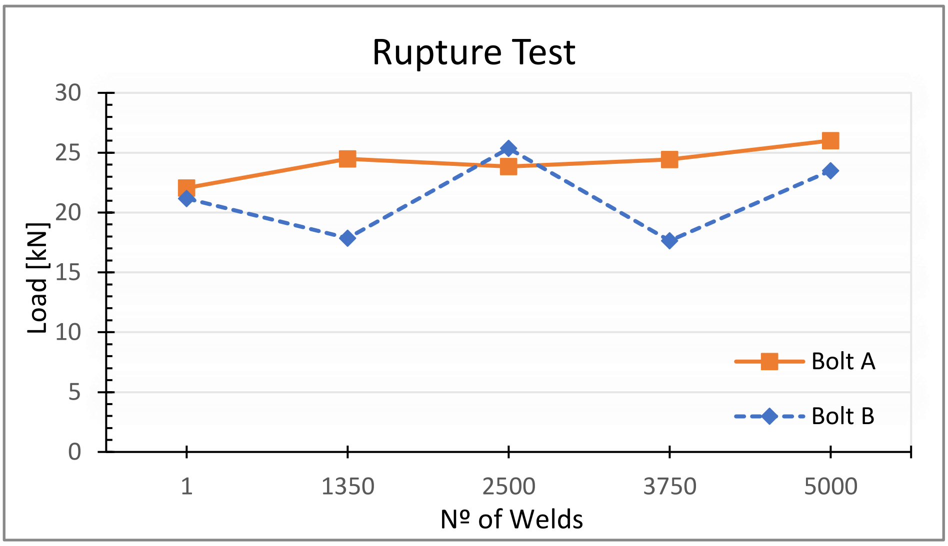


Figure 32 – Graphic representation of rupture test results from the Electrode's Wear Study.

Still, in this chapter, it is important to mention that all the quality control tests (rupture and geometrical) that were performed according to the internal normative were always satisfied during the study.

4.2.3.2 Macrographic analysis of the electrodes

For the electrode macrographs, the results are expressed in Figure 33 for the lower electrode and Figure 34 for the upper one. To note that the macrographs were made on the most worn electrode, in this case the one that performed the *bolt B* weld.

Figure 33 a) shows that for 0 welds, the electrode is new, has the as machined pattern, and has the copper colour aspect, as expected. Figure 33 b) shows that same electrode for 2500 welds. here the electrode does not seem to have worn significantly. It is possible to see pitting, mechanical deformation, and changes in colour. Pitting, which is seen as the formation of holes, is a result of the formation of brittle alloys and oxides that crack due to the presence of Zn, Fe, and Al (Enrique et al. 2019). Zones where the machine pattern disappears, and the surface is smooth as a result from mechanical deformation due to the contact between surfaces under high pressure. The colour that seems to be darker in some zones and a little bit brighter in others is the accumulation of oxides and alloys, which have a decreased thermal and electrical conductivity, forming a thermal capsule (Enrique et al. 2019). Even though all these phenomena start to appear, the machine pattern is still visible in some zones, and overall, the electrode is still not considerably worn.

Figure 33 c) shows that after 5000 welds, the electrode has already undergone significant changes. It is possible to see less pitting, mechanical deformation, changes in colour, and material deposition. Pitting has reduced not only because the copper is a soft material that, with the increase in performed welds, deforms, and starts to reduce the holes, but also because, since the temperatures on the electrode surface increase, it improves the accumulation of oxides and other material., Some steel from the plate starts to accumulate, covering the pits. Even if the pitting has reduced, the overall roughness has increased, reducing the thermal and electrical conductivity even more. The colour became even more heterogeneous due to the higher accumulation of oxides, alloys, and materials.

Analysing the bottom electrode's macrographs, represented in Figure 33, it is possible to draw some extra observations:

- As the number of welds increased, the electrode became increasingly worn, as expected.
- The wear rate from 2500 to 5000 welds is higher than the that from 0 to 2500 welds, which can be justified by the increasing temperatures on the contact surface.
- The electrode still does not appear to have sustained critical damage, as such, it is expected that it can withstand more cycles.

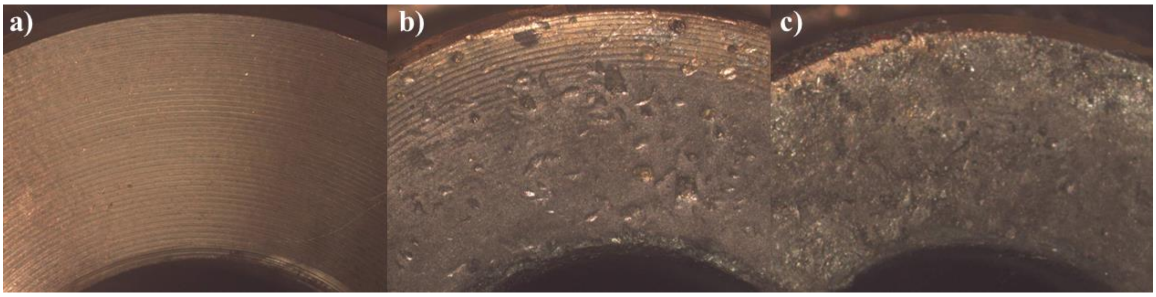


Figure 33 – Electrode’s Wear Study: Bottom Electrode Macrographs: a) 0 welds; b) 2500 welds; c) 5000 welds.

Regarding the upper electrode. Figures 34 a) and d) show that for 0 welds, the electrode is new, has the pattern resulting from its production and has the copper coloration, as expected.

Figures 34 b) and e) show that for 2500 welds, the electrode has some pitting, mechanical deformation, and changes in colour. In this case, two types of pitting were observed. The first, is present in the contact area and results from the formation of the brittle Cu-Fe alloy and oxides (Enrique et al. 2019). The bolt is not coated, so Zn and Al do not interfere in this case. The second type of pitting appears on the periphery (along the perimeter) and is expected to result from the formation of an electrical arc between the bolt's edge and the electrode's surface. Zones where the initial production pattern (seen in Figures 34 a) and d)) disappears, and the surface is smoother resulting from mechanical deformation due to the contact between surfaces under high pressure. The darkening observed, as for results from the accumulation of oxides and Cu-FE alloys, which have less thermal and electrical conductivity, forming a thermal capsule (Enrique et al. 2019). Note that it appears that the colour is darker at the centre region.

This is expected to happen due to the presence of the bolt engravings, given that the temperature reached during the welding is expected to be higher as discussed in Chapter 4.1.5.

With this analysis it was also possible to verify the top electrode had a misalignment, relative to the centre of the bolt. As seen in Figure 34, the wear that appears on the contact area between the bolt and the electrode is considerably misaligned.

Figures 34 c) and f) show that for 5000 welds, compared with 2500 welds, the wear did not change significantly. The pitting on the contact area was reduced due to mechanical deformation that covered the pits, as previously mentioned. The pitting due to the electrical arc increased, as expected. The colour became even darker than after the 2500 welds, due to the formation of more Cu-Fe alloys and oxides. After 5000 welds, the electrode still appears to be in relatively good condition and would be expected to being capable of performing a significant higher number of welds.

Comparing the wear of the upper electrode with the bottom electrode, it is possible to take the following observations:

- The wear rate of the bottom electrode was found to be higher than that of the upper one. This can be explained due to the presence of the galvanized coating on the steel plate, and the fact that temperatures are expected to be higher on the electrode's surface in contact with the plate (the thickness of the bolt is higher than that of the plate), which considerably influences the wear.

- The service life of the electrodes could potentially be defined differently, with the upper electrode being expected to be able to withstand more welding cycles.

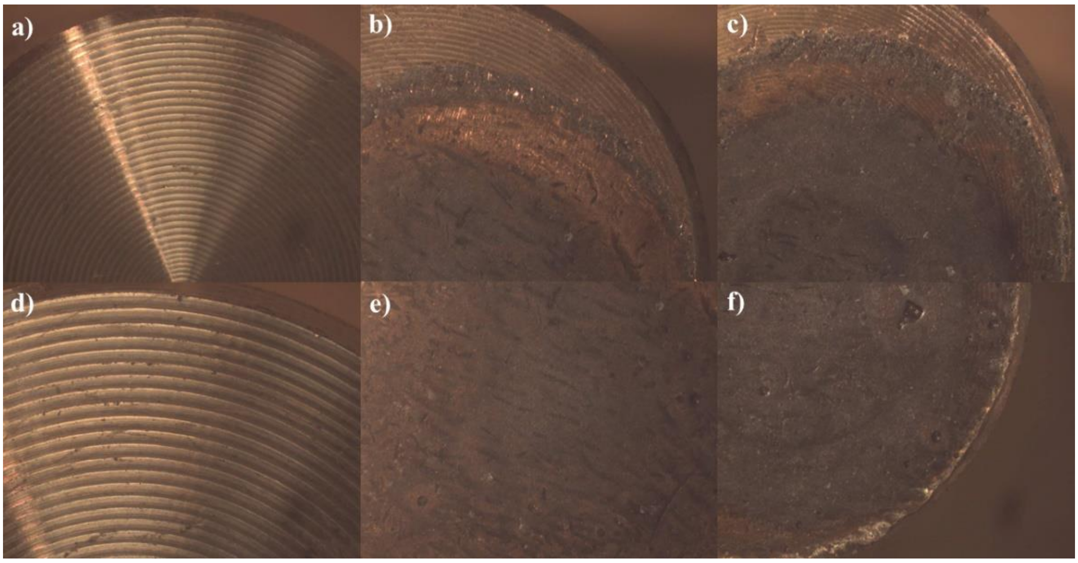


Figure 34 – Electrode's Wear Study: Top Electrode Macrographs: a) and d) 0 welds; b) and e) 2500 welds; c) and f) 5000 welds.

4.2.3.3 Macrographic analysis of the welds

The weld's macrographs are represented in Figure 35 and in Figure 36. It was observed that the two distinct TMAZs are present. One on the bolt's side (the darkest), and another on the steel plate. This phenomenon occurred due to the fact that the bolt's projection was forced to compress against the plate, leading to mechanical deformation at high temperatures. In the bolt, this deformation is visible in Figure 36 by the reduction in the projection height, from 1.25mm to at least 0.67 mm (0.35 + 0.32), and extrusion to the sides. In the steel plate by the penetration 0.32 mm, 0.35 mm, and 0.43 mm in Figure 36 a), b) and c) respectively.

Concerning the TMAZ size, it increased on both components (steel plate and bolt) with the electrode's wear, which is expected since the heat generation increases due to the formation of the thermal capsule (Enrique et al. 2019). That is quantified in Figure 36: the bolt's TMAZ increased from 1.77mm to 1.82mm to 1.88 mm, while the plate's TMAZ increased from 0.97 mm (1.29–0.32) to 1 mm (1.35–1) to 1.15mm (1.58–0.43). Also, the zones where there seemed to be fusion or mixture between materials in the peripheries increased with the electrode's wear.

Based on Chapter 4.1.7 and the macrographs in Figure 37, it was possible to verify the following:

- For 0 welds, the interface between materials is very pronounced, suggesting that the weld type is solid-projection welding, the weakest type of weld.
- For 2500 welds, the interface between materials started to fade, suggesting that the weld type is a mixture of solid-projection welding and embossed-projection welding. A stronger weld than the previous.
- For 5000 welds, the interface between materials started to fade even more, suggesting that the weld type's embossed projection increased in the mix.
- The electrode's wear and consequent formation of a thermal capsule promoted the formation of the embossed projection weld type, improving, in theory, the weld quality.

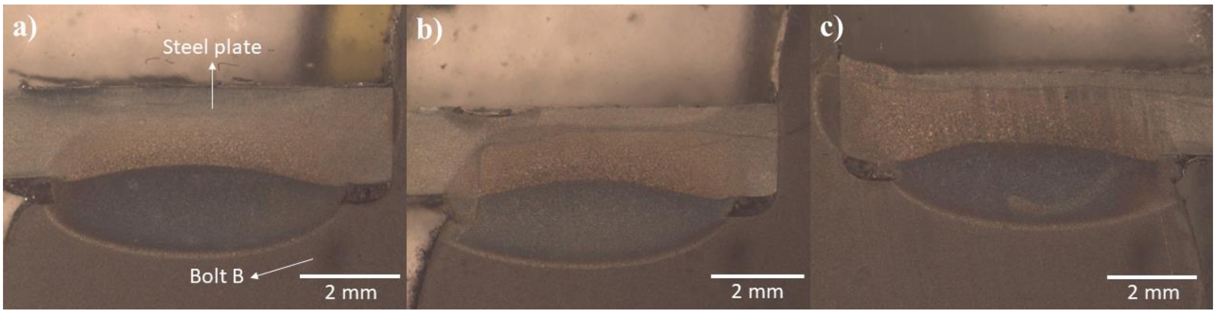


Figure 35 – Electrode's Wear Study: Weld Nuggets Macrographs: a) 0 welds; b) 2500 welds; c) 5000 welds.

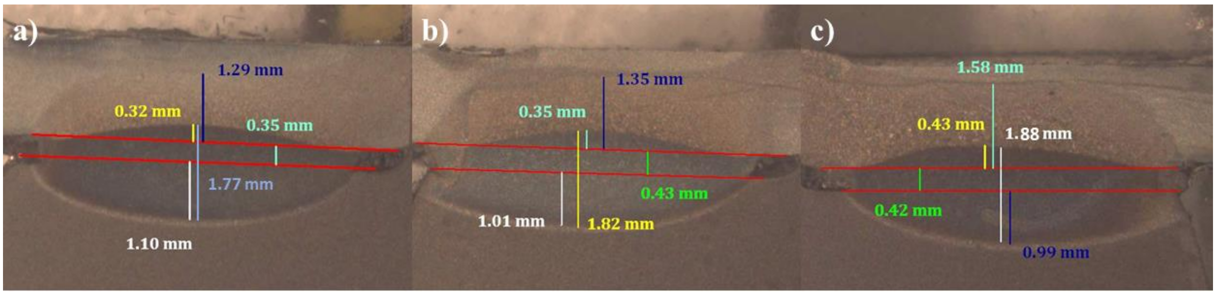


Figure 36 – Electrode's Wear Study: Weld Nuggets Macrographs with measurements: a) 0 welds; b) 2500 welds; c) 5000 welds.

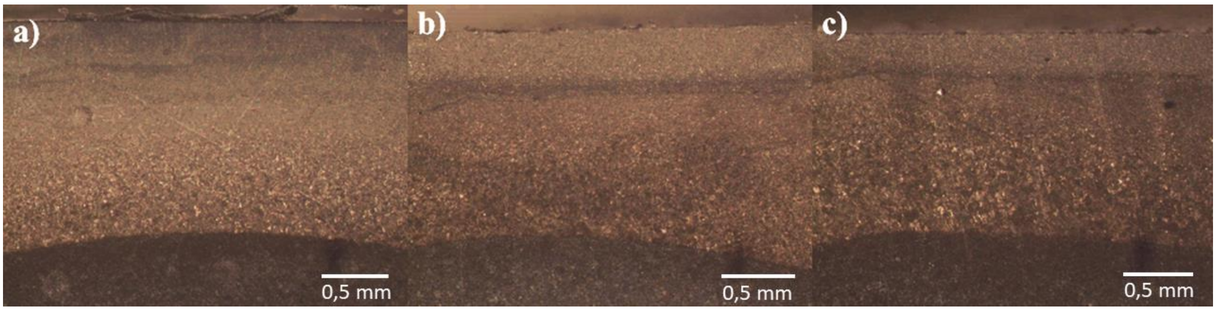


Figure 37 – Electrode's Wear Study: Weld Nuggets Macrographs with the interface in detail: a) 0 welds; b) 2500 welds; c) 5000 welds.

4.2.3.4 Power consumption

The power consumption, as seen in Table 8 and Figure 38, increases with wear almost at a constant rate. This happens because the wear increases the electrical resistance (Enrique et al. 2019). From 1 weld to 5000 welds, the power consumption increased by 7%, which was a growth that is not negligible. Such increase is important to make strategic decisions involving costs and sustainability.

Table 8 – Power consumption results of the Electrode´s Wear Study.

Nº of Welds	Power Consumption [kWh/weld]	Percentage Growth
1	0.02414	7.02%
1250	0.02461	
2500	0.02508	
3750	0.02546	
5000	0.02593	

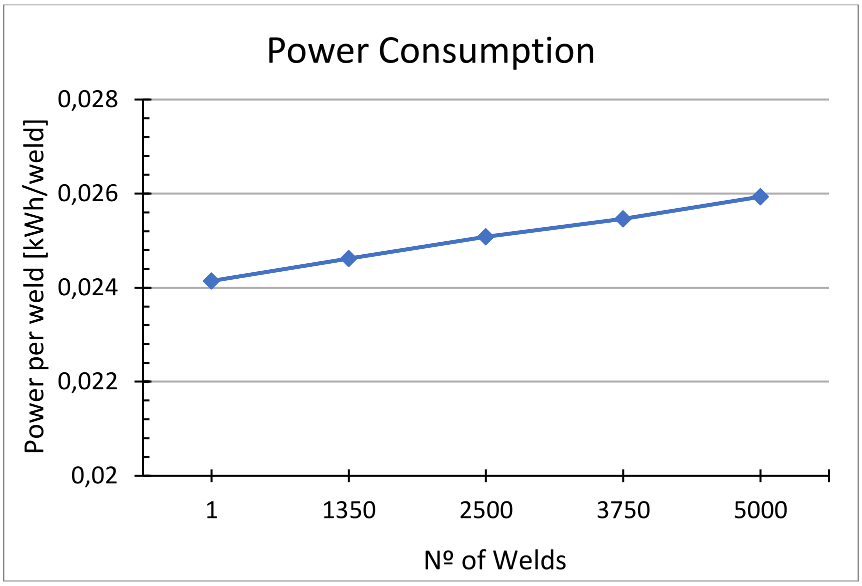


Figure 38 – Graphic representation of Consumption results from the Electrode's Wear Study.

4.2.4 Conclusions

Based on the work carried out and information gathered and presented, it is possible to conclude the following:

- It has become clear that the electrodes can do more than the 2500 welding cycles currently defined. This study demonstrated that the electrodes could produce least 5000 welds within the quality specifications required.
- The weld process itself already has some variability that is difficult to control and predict. Furthermore, this study showed that the bolt defects increased it even more. Consequently, after GESTAMP's request, PECOL started supplying bolts with concentricity and flat bump defects minimized, as seen in Figure 39.

Figure 39 – Supplier's bolt with the defects resolved.

- The wear rate of the bottom electrode was found to be higher than the upper electrode, which suggests that different pre-determined service life for each electrode should be applied.
- The experimental results suggest that the presence of relative electrode wear improves the weld quality. The thermal capsule that the oxides and alloys create increases the resistance, leading to higher heat input and, as a result, higher weld quality.
- Power consumption increases at a constant rate with an increasing number of welds, reaching a maximum of 7% for 5000 welds. Such values will be important to compare the new material proposal to the previous one.

- This study showed that the electrode's wear did not have such a critical impact as common sense suggested. Thus, answering the question made in Chapter 4.2.1, the electrical conductivity could be prioritized over the hardness.

4.3 Alternative material selection for electrodes

At this moment, it was possible to gather the following considerations to select material for the electrodes:

- The most common materials used for PW are classes 2 and 3 (Chapter 2.3.1).
- The Electrode's Wear Study concluded that for the investigated case, the wear is not critical. Consequently, the selection of the material could prioritize the electrical conductivity to the detriment of the hardness (Chapter 4.2).
- For strategic reasons, since these materials are standard and there are few differences between suppliers, Gestamp proposed that the supplier of the chosen material be AMPCOL.

In Table 9 and in Table 10, it is possible to see the selection of materials that AMPCO offers regarding Classes 2 and 3.

Table 9 – Properties of the different possibilities for the new electrode’s material (first table) (METAL 2023).

	AMPCOLOY 88	**AMPCOLOY 89**	**AMPCOLOY 91**
Chemical Composition	97.2Cu 0.5Be 3Co+Ni	97.1Cu+0.4Be 0.3Co 1.8Ni	97.1Cu 0.5Be 2.4Co+Ni
Hardness Rockell/Brinell	103 / 270	98 / 230	97 / 217
Yield Strength [MPa]	682.5	680	551.58
Elongation [%]	14	12	17
Electrical Conductivity [%IACS]	52	69	48
Thermal Conductivity [W/mK]	230	300	210
Young Modulus [GPa]	117	117	117
Max. Working Temperature [ºC]	475	475	450
Class	3	3	3

Table 10 – Properties of the different possibilities for the new electrode's material (second table) (METAL 2023).

	AMPCOLOY 95	**AMPCOLOY 940**	**AMPCOLOY 972**
Chemical Composition	97.2Cu 0.5Be 2Co+Ni	96.4Cu 0.7Si 2.5Ni 0.4Cr	98.8Cu 1Cr 0.1Zr
Hardness Rockell/Brinell	100 / 240	96 / 210	78 / 140
Yield Strength [MPa]	537	517	370
Elongation [%]	17	20	13
Electrical Conductivity [%IACS]	45	48	86
Thermal Conductivity [W/mK]	218	218	310
Young Modulus [GPa]	117	117	112
Max. Working Temperature [ºC]	450	450	500
Class	3	3	2

From the possibilities presented, two materials stood out: AMPCOLOY 89 from class 3 and AMPCOLOY 972 from class 2. Since greater the hardness and electrical conductivity the better, the first one is the best candidate from class 3 due to its balance between its value of hardness (HB 217) with its relatively high value of electrical conductivity (69% IACS). The second is interesting because, despite having a lower hardness, it has very good electrical conductivity (86% IACS).

Since the overall study's objective is to optimize the power consumption without compromising the quality of the produced welds and as seen in Chapter 4.2, the electrical conductivity could be prioritized over the hardness, AMPCOLOY 972 seemed the best option and was selected. Curiously, as seen in Chapter 3.1, the conclusion that originated this project, made by Eng. a Mariana Souto, was that the transition between the two different materials of the electrodes and the electrode holders is a resistance input leading to power dissipation. Since the electrode holders are made of AMPCOLOY 972, this problem is also resolved. The decision was made that this material would be tested, and if it did not comply with the requirements, it would be tested the second one (AMPCOLOY 89).

4.4 Welding parameters

Changing the electrode's material for the chosen alternative will, by itself, reduce the electrical resistance of the system and, consequently, the power consumption. It is also crucial to adapt and optimize the welding parameters for the selected material. This will not only guarantee the consistency and viability of the weld, but also reduce power consumption even further. In this chapter, the approach used to systematically investigate the optimization of the welding parameters will be described.

4.4.1 Preliminary experimental investigation

4.4.1.1 Soft mode VS hard mode

As explained previously during this work, PW has a lot of variables that influence welding. For PW, as Sejč et al. (2020) and others stated, the welding parameters can be divided into two main groups: the ones that originate a soft mode weld and the others that originate a hard mode weld. Hard welding, or fast welding, which uses a high current and high force for a short amount of time; and smooth welding, or slow welding, which uses a low current and tight force for a longer amount of time. These two different combinations of parameters generally lead to differences in the welding quality, strength, and type. Sejč et al. (2020) concluded that the first (hard welding mode) is better in terms of how strong the joint is, approximately two times stronger. This conclusion can vary with each scenario and depends on each welding specification.

Naturally, the first step in this study was to specify the impact of soft and hard modes for the relevant case, drawing inspiration from the findings of the previous study. This would not only enable us to start understanding the parameters influence, but also restrict the immense possibilities of parameters to half (hard or soft parameters). As verified in Chapter 4.1.7, the welding parameters applied by the company correspond to a hard welding mode. So, these parameters (shown in Table 5) will be the starting point. Note that the current can be applied in many ways (a peak or by steps). However, since the type of application of the current, in a peak or by steps, do not have significant impact in PW (Furusako et al. 2019). Regarding the type of application of the current it was assumed to be in a peak, which is more simpler and efficient (Furusako et al. 2019).

For this first approach, the set of parameters and respective results (always for the critical position of the bolts) are represented in Table 11. It is important to note that:

- Hard mode parameters: even though the hard mode parameters (*specimen 1*) were based on the ones already used, they are slightly different because the material (AMPCOLOY 972) has better conductive properties.
- Soft Mode parameters: the initial idea was to reduce in half the current and force applied, use double the welding time to guarantee the soft mode and then, if necessary, adjust some parameters (*specimen 2*). However, 10 kA of current was not able to perform a connection, being 12 kA the minimum current capable of connecting the materials and maintaining the soft mode approach.

Table 11 – Rupture test results for the hard mode and soft mode approaches for parameter definition.

	Welding Parameters			Rupture Test	
Specimen	**Current [kA]**	**Welding Time [ms]**	**Welding Pressure Force [kN]**	**Bolt A [kN]**	**Bolt B [kN]**
1	19.5	200	10	15.69	15.80
2	12	400	5	10.03	9.86

Analysing the results presented in Table 11 and the macros in Figure 40, it is possible to state the following:

- The hard welding mode generates stronger welds than the soft mode. Even though the values are too close for the requirement of 15 kN.

- Figure 40 shows that the different welding mode approaches clearly influences the type of weld. Hard welding mode, Figure 40 b) produces a nugget with a bigger area, with a diameter of 6.93 mm (higher collapsing rate) with fusion bonding on the outside, further from the centre of the bolt, and solid-state bonding on the inside, inner area of the bolt. On the other hand, in soft welding mode, Figure 40 a), the weld nugget is smaller, with a diameter of 4.59 mm, and the welding type is predominantly fusion bonding. Such phenomena are in-line with what has been introduced and discussed in Chapters 2.1.3.2 and 4.1.7.

- Despite the embossed-projection bonding type is stronger than the solid-projection type, it is not possible to determine which weld is stronger only by the weld type (embossed-projection welding or solid-projection welding). The weld nugget size also influences weld strength. Despite the fact that embossed-projection bonding produces a better connection, in this case the weld nugget is smaller, the tensions will be much higher, and the weld will be weaker. On the other hand, even though hard mode produces a mix-type weld (embossed-projection welding and solid-projection welding), which in theory is weaker bonding, the same loads will be distributed over a significantly larger area, consequently generating a stronger weld (Enrique et al. 2019).

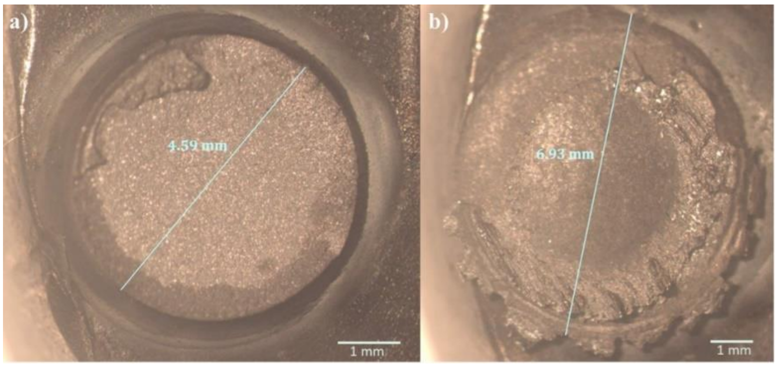


Figure 40 – Weld nuggets macrographs: a) soft welding mode; b) hard welding mode.

Based on this first preliminary analysis, it is possible to conclude that to find the optimal parameters, it is better to take a hard mode approach. Moreover, this approach will also be beneficial to vaporize the galvanized coating, which will diminish the risks of defects forming (Sejč et al. 2020).

Note that, despite the fact that the conclusion made by Furusako et al. (2019) was highly significant, due to the considerable variability associated with this specific process, not only would the search for the optimal point be very difficult or not achievable within the time frame and resources for the present work , but also the probability of the conditions varying, and the weld failing was not acceptable from a quality standard perspective. However, the results obtained, and the conclusions drawn from using this approach was still useful for other welding equipment within the company, which use the same type of weld and conditions.

4.4.1.2 Weld nugget efficiency and strength

Based on the knowledge acquired, the experiments carried out and the conclusions drawn in the present work, particularly in the sub-chapters 2.1.3.2, 4.1.7, and 4.4.1.1, it is possible to describe the ideal weld nugget for the specific weld being investigated. Some of the characteristics that would characterize an ideal nugget are large welding area to distribute the loads, reducing the concentration of tensions and the weld type should be fully embossed-projection welding (fusion).

Such characteristics demand a challenging set of parameters, since the force and the current used should be enough to generate a high collapse rate, and the welding time should be enough to completely fuse the projection with the plate. All this without promoting the occurrence of defects such as expulsion of flash material, which was found to be a considerable hard balance. This ideal scenario requires a lot of energy to fuse all the material, is very sensitive to variability and defects, and, since the mix-type weld already sustain the required loads, it will be stronger than necessary. So, given the challenges, difficulties, and energy consumption, it makes sense to aim for a more efficient weld nugget, which would be characterized by the following:

- Correct balance of the two welding types, embossed-projection welding only in the necessary amount to combine with the solid-projection welding sustain the required loads.
- A weld nugget’s area large enough to distribute the loads.

This effective weld nugget ought to resemble both the ones the company is currently producing and the one that came about as a result of the hard welding mode. This will reduce the appearance of defects, increase the resistance to variability, and reduce power consumption while maintaining the desired mechanical requirements. So, this would be the type of nugget that the parameter optimization carried out in the study should yield.

4.4.2 Welding parameters optimization study – Taguchi method

4.4.2.1 Objective

The main objective of this study is to determine the desired optimal set of welding parameters without requiring an extensive analysis, with minimal costs and machine stoppage time. Taguchi´s method perfectly fits these industrial necessities and provides reasonable statistical results, given the constrains it aims to respect.

It should be noted that due to cost constraints and the associated downtime of the machinery, this study only allowed for a single experiment to be conducted for each set of parameters. Even though it is expected that the study will be highly influenced by experimental errors and variabilities, this study could provide significant results and insights into quantifying how the process parameters influence the produced weld.

4.4.2.2 Planning

The first step in this method, and the most important, is to correctly identify the controllable and response variables. Then, define the orthogonal matrix with the experimental combinations with the parameters set within the parameter windows pre-defined.

The controllable variables in the case being studied, like in many others related to welding, are the welding current, welding time, and welding pressure force. The response variable is the maximum load resulting from the rupture test. Due to cost and time limitations, it was only possible to make the study for three levels combined in a L9 Taguchi orthogonal matrix (seven experiments). The three levels for each variable are represented in Table 12 and were selected based on the following:

- Current: The starting point was the current used in Chapter 4.4.1.1 for the hard welding mode, and other two levels with lower current were selected. This approach was taken to reduce power consumption.
- Welding Time: The starting point was the welding time used in Chapter 4.4.1.1 for the hard welding mode. However, in this case, the other two levels are defined with a longer welding time because decreasing it would lead to the thermal power generated not being enough to produce a sound weld.
- Welding Pressure Force: The starting point was the welding pressure force used in Chapter 4.4.1.1 for the hard welding mode. In this case, the other two levels are lower given that AMPCOLOY 972 is a soft material, and the lesser the welding pressure force, the lesser would be the electrode mechanical deformation, which would increase it durability and efficiency.

Table 12 – Taguchi's orthogonal matrix for the welding parameter optimization study.

Level	Welding Current [kA]	Welding Pressure Force [kN]	Welding Time [ms]
1	16.5	6	200
2	18	8	260
3	19.5	10	320

In Table 13, it is represented not only the L9 orthogonal Taguchi's matrix based on the levels represented in Table 12 but also the response values that are the results from the rupture test for each combination of parameters.

Table 13 – Experimental rupture test results according to Taguchi's orthogonal matrix.

Run No.	Welding Current [kA]	Welding Pressure Force [kN]	Welding Time [ms]	Bolt A [kN]	Bolt B [kN]
1	16.5	6	10	9.53	13.45
2	16.5	8	13	20.32	12.86
3	16.5	10	16	12.49	10.67
4	18	8	10	14.97	14.32
5	18	10	13	17.02	16.64
6	18	6	16	21.66	14.73
7	19.5	10	10	20.15	13.78
8	19.5	8	13	17.15	16.04
9	19.5	6	16	15.98	19.58

4.4.2.3 Statistical analysis

For this study, two types of analyses were performed: a signal-to-noise (S/N) ratio analysis to select the optimized set of parameters and an ANOVA analysis to rank the parameters by influence/contribution.

The main effects plots for the S/N ratio are represented in Figure 41: Figure 41 a) for *bolt A* and Figure 41 b) for *bolt B*.

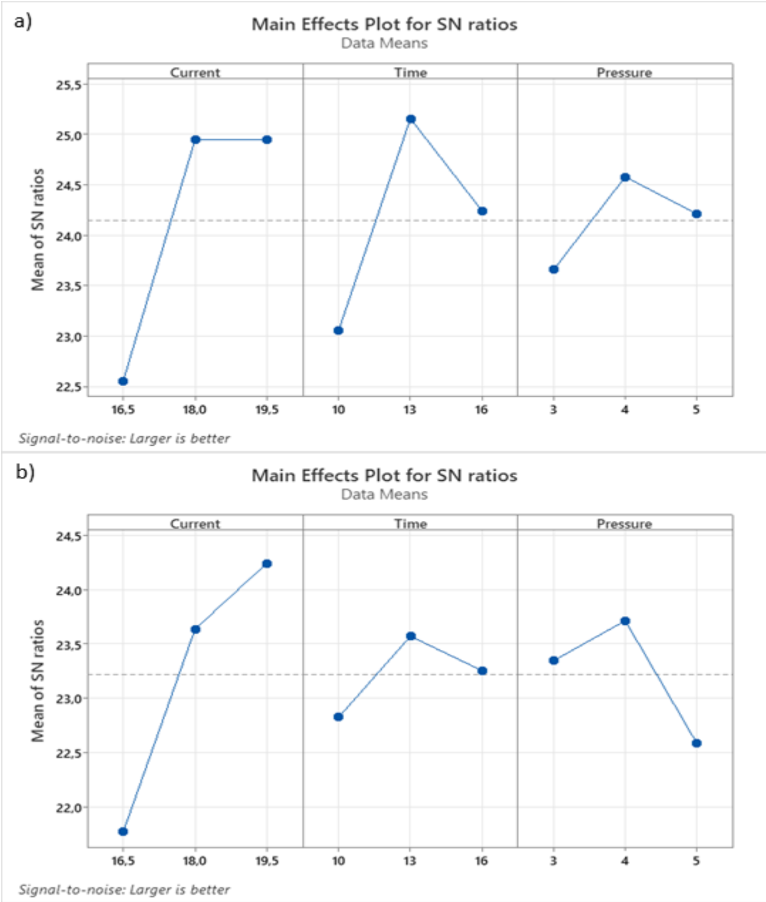


Figure 41 – S/N ratio analysis curves for both bolts: a) *bolt A*; b) *bolt B*.

From these graphs, it is possible to conclude that, according to the Taguchi method, the optimal set of parameters, which are the parameters that give a higher Mean of SN Ratios value and likely lead to a better weld, are the ones represented in Table 14 (Peace 1993; Minitab 2023b). Note that, for *bolt A* (Figure 41 a)) since the optimal value for current could be 18 kA or 19,5 kA, it will be assumed that the best is 18 kA due to energy savings and that *Time* is in cycles (1 cycle = 20 ms) and *Pressure* in bar (for the machine's pneumatics 1 bar = 2 kN) .

Table 14 – Optimized set of welding parameters according to Taguchi´s method.

	Optimized Welding Parameters		
Bolt	**Current [kA]**	**Welding Time [ms]**	**Welding Pressure Force [kN]**
A	18 or 19.5	260 (13 cycles)	8 (4 bar)
B	19.5	260 (13 cycles)	8 (4 bar)

The results of the ANOVA analysis are represented in Tables 15 a) (*bolt A*) and in Table 15 b) (*bolt B*). Analysing the results, it is possible to see the following:

- *Bolt A* (Table 15 a)): the parameter that most contributed/influenced the welding strength was found to be the current, followed by the welding time, and finally the weld pressure force.
- *Bolt B* (Table 15 b)): the parameter that most contributed/influenced the welding strength was the current by far, followed by the weld pressure force, and lastly the welding time.
- The contribution of the residual error in both cases was considerably significant, which was expected since it was not possible to perform more than one experiment for each set of parameters.
- The results suggest that, even though the contribution, in both cases, of the welding time and welding pressure force was relatively low, for bolt B (Table 15 b), where there are flatness defects, the results showed that the pressure force has a higher impact than welding time. If it would be necessary to manipulate the parameters to guarantee the weld quality under flatness defects, before spending more energy increasing the welding time, it would be more efficient and effective to increase the welding pressure force.

Table 15 – ANOVA analyses results: a) *bolt A*; b) *bolt B*.

a)

Source	**Seq SS**	**% Contribution**
Welding Current	26.001	67.98
Welding Time	2.262	5.91
Welding Pressure Force	1.116	2.92
Residual Error	8.870	23.19
Total	38.248	100

R-Sq	R-Sq(adj)
76,81%	7,24%

b)

Source	**Seq SS**	**% Contribution**
Welding Current	9.9206	55.61
Welding Time	0.8379	4.70
Welding Pressure Force	1.9678	11.03
Residual Error	5.1141	28.66
Total	17.8404	100

R-Sq	R-Sq(adj)
71,33%	0,00%

4.4.2.4 Confirmation test

After all the analyses, it was necessary to make a confirmation test to evaluate if the Taguchi method gave the results as expected and, if not, what could be wrong. The best way to do so is to predict the expected response for the optimal set of parameters and compare the values obtained experimentally. The predicted values and the experimental values are represented in Table 16 for both optimal scenarios.

The differences between the prediction and the experimental result are about 9% in both cases, which is a relatively low deviation, given all the variabilities associated with the process. Also note that, even though the prediction had some error, the requirement of 15kN was satisfied for both cases.

Table 16 – Taguchi's confirmation test results.

	Welding Parameters			Rupture Test [kN]	
Bolt	**Current [kA]**	**Welding Time [ms]**	**Welding Pressure Force [kN]**	**Prediction**	**Experimental**
A	18	260	8	19.96	21.73
B	19.5	260	8	17.88	16.28

Aside from the Taguchi method, due to the proximity of the *bolt B* rupture value (16.28 kN) to the required limit (15 kN), to approve this set of parameters, it was necessary to prove that this minimum only happens for the critical position and not for the usual random positioning of the bolts. For that reason, a weld made with those same parameters was performed in a random positioning, which yielded a rupture for *bolt B* at 20.29 kN, which showed that this set meets the mechanical requirements.

4.4.2.5 Conclusions

Despite all the variability and errors, it is possible to conclude that the Taguchi method applied for the case under study was capable of providing a set of welding parameters for the worst scenarios that satisfied the mechanical performance requirements. Thus, the welding parameters for the new electrode's material, AMPCOLOY 972, were defined.

4.5 Proposed electrode wear study

4.5.1.1 Objective

Although it was verified in Chapter 4.2 that the electrode´s wear is not as critical as it might be assumed to be initially, the electrode material could have lower mechanical properties, namely hardness, and better conductive properties, it is not enough to conclude that the new electrodes in AMPCOLOY 972 with the optimized parameters will endure the same welding cycles and have the same performance as the previous one.

So, the objective of this study is not only to evaluate the durability and performance of the new electrodes, comparatively to previous electrode material, but also to guarantee the reliability of the application of the new electrodes and welding parameters.

4.5.1.2 Methodology

The main objective of this study was to evaluate the performance of the electrodes in production. To make this analysis, the following procedure was adopted:

- The electrode's operating life was divided into stages of 1250 cycles for an analysis similar to the study in Chapter 4.2, and depending on the results, the study would proceed or be altered.

- A rupture test was performed, according to the required specifications, for the defined stages corresponding to 1, 1250, 2500, 5000, 6250, 7500 and 8000 welds. To ensure the representativeness of the results, three tests were performed for each stage, and the average was determined.

- The power consumption for each of the stages was measured.

- In this study, the bolts were positioned randomly as a natural result of the manufacturing process.

- The water-cooling flow was kept at a value higher than 15, which is the value defined as the minimal acceptable for operation (around 29 l/min all study).

- Photos of the electrode's wear were taken at 0, 2500, 5000, and 8000 welds to evaluate the electrode's wear.

Due to setup constrains of the welding machine that were not possible to solve in the course of the project, it was not possible to define two levels of current: 18 kA for *bolt A* and 19.5 kA for *bolt B*. Hence, the current had to be defined at 19,5 kA for both bolts. This constraint will naturally result in higher power consumption, which might be avoided in the future.

4.5.1.3 Results

The study went on for 8000 cycles. It stopped because, as will be seen, at that point the strength of the weld started to decrease, and both the power consumption and electrode wear increased significantly. Such conditions would not be beneficial.

Starting with the rupture test, the results are presented in Table 17 and summarized in the graph represented in Figure 42. Analysing the results, it is possible to verify the following:

- *Bolt A*'s welds have higher strength than *Bolt B*'s welds for the same welding parameters, which can be explained since *Bolt B* is welded to a surface with more flatness defects (see Chapter 4.1.3).

- During all the electrode's service life investigated service life (up to 8000 welds), the weld satisfied the requirements.

- Despite the fact that, after 2500 cycles, the strength of the weld decreased, the study continued not only because it was expected that the weld would stabilize or even improve, based on the previous wear study made in Chapter 4.2, but also because the power consumption did not change, which combined with the visual observation of the electrodes suggested that it was not the wear that caused that variation.

- At 8000 cycles, the strength decreased, but at this point the power consumption was increasing significantly, suggesting that the wear started to have a significant impact on the quality of the weld. Hence, it was concluded that from there on, it would no longer be viable to continue increasing the number of welds performed.

Table 17 – Rupture test results of the Electrode´s Wear Study

Rupture Load [kN]	**Bolt A**				**Bolt B**			
Nº of Welds	Sample 1	Sample 2	Sample 3	Average	Sample 1	Sample 2	Sample 3	Average
1	18.01	22.05	20.16	**20.27**	17.02	22.03	21.05	**20.03**
1250	22.86	17.72	24.46	**21.68**	23.05	16.53	16.71	**18.76**
2500	17.93	18.38	23.52	**19.94**	16.13	18.08	16.13	**16.78**
3750	20.51	21.64	19.25	**20.47**	17.39	17.58	17.26	**17.41**
5000	25.44	25.48	19.68	**23.53**	20.17	24.37	17.66	**20.73**
6250	22.69	24.70	24.80	**24.06**	20.47	23.40	18.78	**20.88**
7500	23.14	23.77	19.90	**22.27**	17.08	22.39	18.67	**19.38**
8000	22.94	24.08	16.03	**21.02**	23.24	170.4	15.82	**18.70**

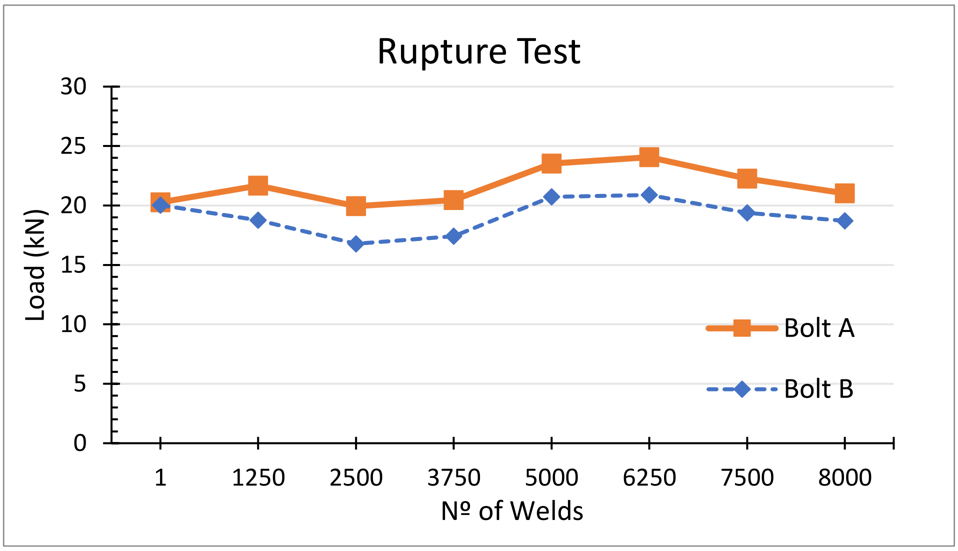


Figure 42 – Graphic representation of rupture test results from the Electrode's Wear Accompaniment Study.

Concerning power consumption, the results are presented in Table 18 and schematically shown in Figure 43. From this data, it is possible to observe the following:

- Until 5000 welds, the electrodes of this new material were not sensible to wear, and the power consumption was maintained or even slightly decreased (- 0.58%).
- The power consumption was steady until 5000 welds. From then on, it started increasing (~ 3%).

Table 18 – Power consumption results of the Electrode´s Wear Study

Nº of Welds	Power Consumption [kWh/weld]
1	0.02168
1250	0.02169
2500	0.02163
3750	0.02153
5000	0.02150
6250	0.02171
7500	0.02216
8000	0.02236

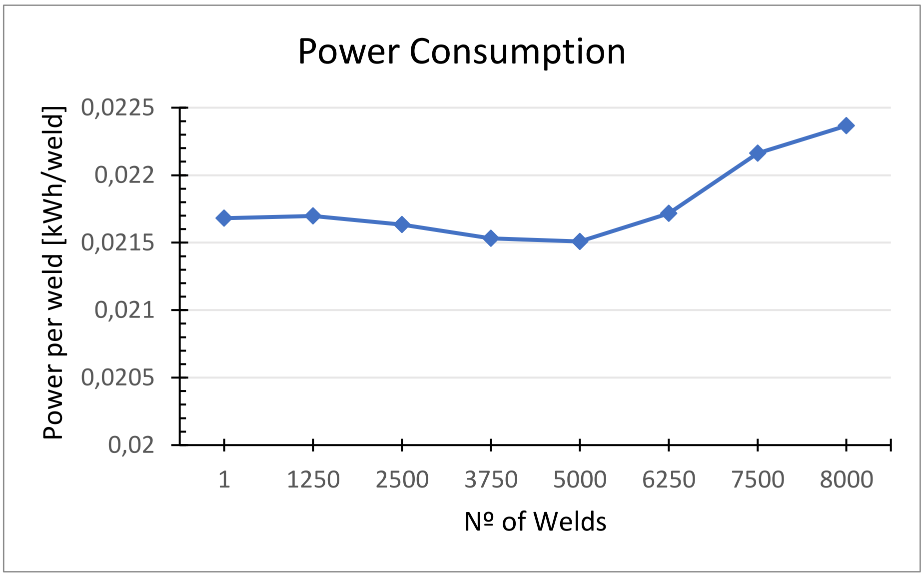


Figure 43 – Graphic representation of Consumption results from the Electrode’s Wear Study.

Finally, the images presenting the wear of the electrodes are shown in Figure 44. Based on these images, it is possible to state the following:

- Naturally, the electrode underwent some wear from 0 to 2500 welds, but not significantly. The oxides and alloys started to accumulate, and pitting started to appear but not critically (Figure 44 b) and f)). Combining this observation with the power consumption, it is possible to state that this worn layer did not have a great impact on the weld.
- From 2500 to 5000 welds, the differences are slight. The top electrode appears more mechanically deformed, and the bottom one has a little more oxides and alloys, but nothing significant (Figure 44 c) and g)). This also makes sense compared with the power consumption. Like it did not very significantly, the wear did not also. Note that the main reason for the top electrode to deform (Figure 44 c)) is not because the electrode is softer. It is because it is not aligned with the bolt (Association 1942).

- From 5000 to 8000 welds, the top electrode deformed more, but not critically (Figure 44 d) and h)). On the other hand, the bottom electrode wore rapidly from 5000 to 8000 welds, and the formation of alloys and pitting increased, leading to an increase in the temperature at the interface, and consequently, the material of the steel plate started to stick more. This increase in wear justifies the increase in power consumption due to the increase in contact resistance (Enrique et al. 2019).

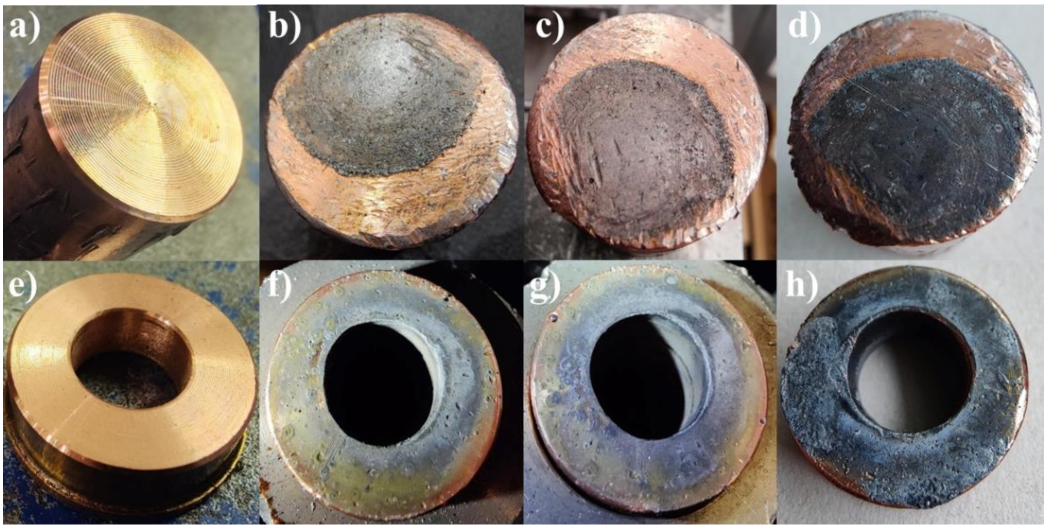


Figure 44 – Electrode's Wear Accompaniment Study: a) and e) 0 welds; b) and f) 2500 cycles; c) and g) 5000 welds; d) and h) 8000 welds.

4.5.1.4 Conclusion

Based on the information presented, it is possible to conclude the following:

- The alternative material proposed for the electrodes can produce welds that satisfy the requirements for up to 8000 welds.
- It was defined that 8000 welds was a reasonable limit given that the weld's strength decreased, and the power consumption increased significantly, suggesting that the wear started to have a significant impact on the quality of the weld.
- The electrode's wear was not significant until 5000 welds, as well as for the power consumption. But from there on, it started to become more serious and critical.
- Once alignment issues are resolved, it is expected that the top electrode's service life could be higher than 8000 welds.
- The main objective of this study was accomplished. It was not only possible to define the new electrode service life as 8000 welds but also to gather important data about the wear, weld strength, and power consumption to compare with the previous, currently standard, material.

4.6 Comparison with the current

Finalized the definition of the new electrodes, their welding parameters, and their durability. It's time to gather all the experimental data and compare the electrodes in use and the solution proposed to evaluate if there will be a difference and assess its cost-benefit. Note that in this chapter the welding strength will not be object of comparison between the two materials, since for both cases the weld performance requirements are satisfied.

4.6.1 Productivity

Starting with the productivity gains. Considering that the electrodes made by AMPCOLOY 95 have a service life of 2500 welds and the AMPCOLOY 972 ones achieved a service life of 8000 welds:

- This solution will reduce the downtime of the welding equipment due to electrode change time by 3.2 times. In full production, it is expected that Gestamp will manufacture 777 600 parts per year. For AMPCOLOY 95 electrodes, this corresponds to 309 stoppage times, and 96 stoppage times for AMPCOLOY 972. Considering that it takes around 10 minutes per setup change, this results in a reduction of stoppage time by 2130 minutes (35 hours and 30 minutes). This gain can be transformed in two ways by the company: first, if the company intends to produce more pieces per year, considering that one piece takes around 12 seconds to manufacture, it will be possible to increase production by 10 650 parts per year; and the second, and possibly the most interesting for the company, is the cost savings related to the operator. According to company data, the 35 hours and 30 minutes saved will result in a reduction of €381,63 per year.

- This change will also reduce the workload on the line managers, who are responsible make perform electrode setup changes, and reduce the wear and the risk of damaging the equipment components during change. Also reduce the workload of the tool shop department, which will result in a reduction of 3.2 times in the need for electrode production or reconditioning.

4.6.2 Electrode's manufacturing costs

Regarding the manufacturing costs of the electrodes produced with both materials, for the present comparison, two points must be considered, the material cost and the savings due to the difference in the corresponding service life. Analysing the suppliers and the data form the company, it was possible to gather the following information:

- From AMPCOLOY, the supplier of the material, it was determined that AMPCOLOY 972 costs less 30% than AMPCOLOY 95, given the difference in allowing elements;

- The overall cost (material, machine wear, power consumption, working personnel, and refitting) to manufacture electrodes from AMPCOLOY 95 is €21.4 and €12.8 for the upper and bottom electrodes respectively;

- According to the company's data, it is expected that consumption for 2023 will be 91 bottom electrodes and 70 upper electrodes in AMPCOLOY 95. This expectation could be generalized from 2023 onward;

- The quantities of material necessary to produce each electrode are represented in Table 19. This was necessary to understand the cost savings due to the difference in material cost. Note that the quantities necessary to make AMPCOLOY 972 are higher because the supplier, AMPCOLOY, only has rods of 32 mm in diameter, while for AMPCOLOY 95, it supplies rods of 30 mm in diameter.

Table 19 – Mass necessary to produce each electrode in the respective materials.

	Top Electrode	Bottom Electrode
AMPCOLOY 95	0.3102 kg	0.1055 kg
AMPCOLOY 972	0.3572 kg	0.1214 kg

With all this information and some calculations, it is possible to obtain the results represented in Table 20 for the AMPCOLOY 95 electrodes.

Table 20 – The cost of manufacturing each AMPCOLOY 95's electrode per year.

AMPCOLOY 95	Price/u. [€]	Number of expected electrodes per year	Cost per year [€]
Bottom Electrode	12.80	91	1164.8
Top Electrode	21.40	70	1498
Total	-	-	2662.8

For the electrodes in AMPCOLOY 972, it is necessary to take into consideration that they will be consumed 3.2 times less than as many of the currently used electrodes and that the material is 30% cheaper. With this, it is possible to obtain the costs represented in Table 21. It should be noted that the column titled "Material savings per electrode [€]" represents the monetary savings per electrode achieved through the transition to AMPCOLOY 972.

Table 21 – The cost of manufacturing each AMPCOLOY 972's electrode per year.

AMPCOLOY 972	Price/u. [€] (AMPCOLOY 95)	Number of expected electrodes per year	Material savings per electrode [€]	Cost per year [€]
Bottom Electrode	12.80	91/3.2=28	-0.73	337.96
Top Electrode	21.40	70/3.2=22	-2.14	423.72
Total	-	-		761.68

Making the difference between both costs, it is possible to conclude that due to the change in material, the manufacturing costs decreased from €2662,8 to €761,68, with total savings of €1901,12 per year.

4.6.3 Power consumption

Lastly, it is important to compare the power consumption. As is possible to see in Figure 45, where both energy consumptions are compared, the power consumption for the AMPCOLOY 972 electrodes does not change significantly with usage until 5000 welds. On the other hand, for AMPCOLOY 95, it increased by 7%, and it would be expected to continue to rise with the number of welds. This a critical advantage for the AMPCOLOY 972 electrodes. Besides this, Table 22 shows that, right at the beginning from the first weld, there was an 11,36% reduction in energy consumption and this difference increased to 20,57% less power per weld at 5000 welds.

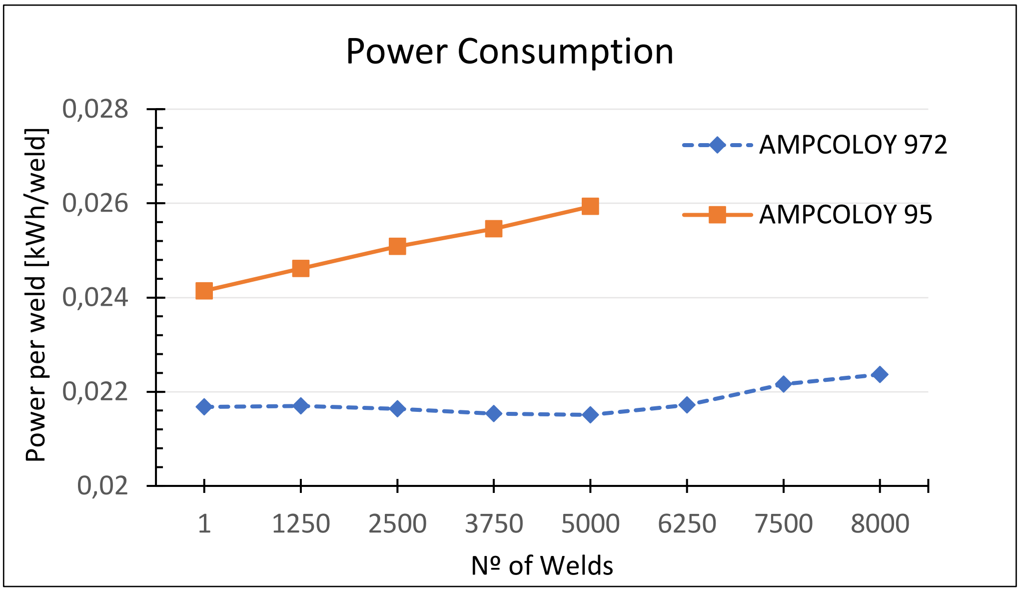


Figure 45 – Graph that schematizes the comparison in power consumption.

Table 22 – Comparison in power consumption for both materials.

Nº of Welds	Power Consumption Savings [kWh/weld]	Difference between AMPCOLOY 95 and 972
1	0.002462	- 11.36 %
1250	0.002917	- 13.45 %
2500	0.00345	- 15.95 %
3750	0.003930	- 18.25 %
5000	0.004424	- 20.57 %

For the purpose of comparison, a realistic and approximate approach is to consider that the service life of AMPCOLOY 972 electrodes (8000 welds) is equivalent to 3.2 service lives of AMPCOLOY 95 electrodes (2500 welds). This implies dividing the service life of AMPCOLOY 972 into 3.2 intervals and comparing each interval with the service life of AMPCOLOY 95 as depicts in Table 23.

Table 23 – Overall energy savings estimation.

Analysis Interval	Nº of Welds AMPCOLOY 972	Nº of Weld AMPCOLOY 95	Power Consumption savings [kWh/weld]	Percentage Growth from AMPCOLOY 95 to 972
1	1	1	0.002462	- 11.36 %
	1250	1250	0.002917	-13.45 %
	2500	2500	0.003450	- 15.95 %
2	2501	1	0.002587	- 11.60 %
	3750	1250	0.003084	- 14.32 %
	5000	2500	0.003575	- 16.62 %
3	5001	1	0.002633	- 12.24 %
	6250	1250	0.002898	- 13.34 %
	7500	2500	0.002922	- 13.18 %
4	7501	1	0.00198	- 8.94 %
	8000	500	0.001959	- 8.76 %

The results of these previous analyses are summarized in Table 24. In this table, the mean values for each analysis interval for the power and percentage savings are represented since it facilitates the overall calculations without compromising the accuracy of the results. Please note that the calculation utilized an average price of 0.15 €/kWh, representing the cost of electricity in Portugal for the year 2023. It has been determined that a savings of €3.47 can be achieved for each cycle of 8000 welds. When comparing this to the previous material, the mean percentage savings amount to 13.23% (weighted average) over the course of the service cycle. As projected by the logistic department, a total production of 771,600 pieces per year is anticipated for both references 1 and 2. Consequently, this translates to a total annual savings of €336.59 per year.

Table 24 – Energy and monetary savings resulted from the material change.

Analyses Interval	Mean Power Consumption Savings [kWh/weld]	Mean Percentage Growth from AMPCOLOY 95 to 972	Nº Welds	Savings considering 0.15 €/kWh
1	0.002956	- 13.55 %	2500	1.12 €
2	0.003042	- 14.11 %	2500	1.14 €
3	0.002817	- 12.92 %	2500	1.06 €
4	0.001970	- 8.85 %	500	0.15 €
Total	-	-	8000	3.47 €

4.6.4 Overall earnings

To better understand the impact that the choice of material for the electrodes has, an overview of all the savings and changes were compiled into Table 25. To highlight the total savings, those are expected to be approximately 2620 €/year, just for the weld equipment and production series analysed.

The savings obtained from the present work exceeded what was initially expected. However, it can be even greater if issues such as flatness of the steel part, electrode misalignment, and consistency of the bolts supplied are also tackled and minimized.

Table 25 – Compilation of all the savings resulting from the material change.

	AMPCOLOY 95	**AMPCOLOY 972**	**Savings [€/year]**
Productivity	-	3.2 times reduction of stoppage time	381.63
Electrode's Manufacturing Costs	2662.80 €/year	761.80 €/year	1901.12
Power Consumption	-	- 13.23 % - 3.47 €/8000 welds	336.59
Total	-	-	**2619.34**

5 Methodological standard for application in other machines

From the start of the present work, the company expected that with the work done to this point, it would be possible to develop a methodological standard for application in other welding equipment besides the one being investigated. However, as it was learned based on the work developed, due to the specificities of each machine and the details of each process, it would be risky to try to generalize a methodological standard for all at once. So, it was defined that the methodological standard should resemble an overall guide on how to approach other studies on other machines to optimize their processes.

An approach that is proposed it to guide the optimization of other machines is to read the study made in the present work and understand the foundation of each decision and the reason behind each experiment. Given this, the following set of guidelines were defined and proposed:

1. Study the welding process object of investigation and ensure a deep understanding on how each welding parameter influences the weld quality and its defects and how other variables (e. g. setup) can affect it. It is important to note that projection welding has considerable differences from spot welding and, as shown in the work presented, first approaches and comparisons can be misleading, for example in what concerned the wear of the tools and its effects.

2. When understanding of the welding process and its specificities is obtained, a more in-depth study the machine should be performed, analysing the manufacturing process, and identifying its flaws and the conditions behind the possible defects.

3. After understanding the process, the machine and all the nuances involved. All the identified issues should be object of discussions with the responsible maintenance team. If it is not possible to solve those issues with such discussions, the study should continue by evaluating how the wear of the electrodes impacts the weld. After that, an alternative material should be chosen, taking into consideration the dichotomy between conductivity and mechanical properties.

4. An optimization of the welding parameters for the selected material should be performed. The statistical approach using Taguchi Method can be very practical and relatively simple to apply. Despite this, other methods could be more valuable to guide a deeper or more with ranging investigation where more variables and/or process responses are of interest (e.g. central composite design).

5. Testing and a comparison of a proposed new alternative material with the previous one must be done, to ensure the change is beneficial enough. If it does not, points 4 and 5 should be repeated for the other material possibilities until the results satisfy an intended optimization.

Note that these guidelines are numbered, and it is advised that this order be respected.

Given all the nuances and variables involved in an optimization process like this one, these general guidelines would already prove to be a success if at least it could provide an overview of what can be expected and help start the optimization.

6 Conclusions and future work

In conclusion, the collaborative project undertaken by Gestamp Cerveira in partnership with INEGI and FEUP to explore new materials for resistance welding consumables has yielded highly successful and impactful outcomes. The primary objective of the project was to address the pressing need for innovation in electrode materials, aiming to reduce energy usage, prices, and waste associated with resistance welding. The following conclusions were drawn during the course of the project:

- Unexpected paradigm shift in the understanding of electrode wear. Contrary to initial company assumptions, it was found that the wear did not necessarily correlate with its criticality in spot welding. Prioritizing conductivity over hardness proved advantageous. So AMPCOLOY 972 was selected as the new electrode material based on its very good electrical conductivity.

- The weld nugget is a mixture of embossed-projection welding (fusion) on the outside diameter and solid-projection welding (diffusion bonding, forging) on the inner diameter area.

- Optimized set of parameters Taguchi's method: current 19.5 kA, welding time 260 ms, and welding pressure force 8 kN.

- AMPCOLOY 972, which is 30% more cost-effective than the previous one (AMPCOLOY 95), resulted in a remarkable 3,2 times reduction in electrode consumption, a 13.56% decrease in power usage, and a reduction in machine stoppage time. These improvements enabled a total annual savings of 2620 euros.

- The weld quality is influenced by both flatness defects in the steel plate and geometrical defects in the bolt. These factors have a more significant impact when they occur together.

As for future work, it is recommended to optimize other machines and welding processes to evaluate the differences and importance of the established guidelines. Additionally, repairing machine misalignments and flatness issues and assessing the real impact of bolt engravings would further enhance savings and efficiency.

In conclusion, the project's success in introducing new electrode materials for resistance welding consumables, the unexpected insights regarding electrode wear, the significant energy savings achieved. These findings provide a strong foundation for future advancements in resistance welding and underscore the importance of collaborative research and development efforts within the industry.

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