BIMETALLIC MATERIALS WELDING AND ANALYSIS FOR BATTERY PACKS OF ELECTRIC VEHICLES

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ABSTRACT

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Due to the issue related to climate change and excessive co2 emission automakers are moving towards Electromobility. Battery-pack, which is made up of thousands of cells joining together, is a source of power for the electric vehicle. Effective joining technology between the battery cell tab and Busbar enhances the overall electro-mechanical performance of the battery pack and eventually electric car. This thesis aims to Investigate the electrical performance of the Bimetallic Joint between the Battery cell tab and the Busbar.

Literature Review reveals different joining technologies used in the industries to join dissimilar materials for Battery cell tabs to busbar joining. The Resistance spot welding method is used in this Research to join the dissimilar materials by using Sunstone CDDP-A resistance spot welding machine. Experiments were conducted to check the weldability of Dissimilar different materials. A microanalysis of Welded Joint between Nickle and Nickle plated steel was done, and an electrical performance was evaluated.

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With sincere thanks,

Shivam Dave

SYMBOLS AND ABBREVIATIONS

Roman characters

A	Area	[mm]
H	Heat	[J]
I	current	[A]
R	resistance	[Ω, mΩ]
T	temperature	[ºC]
t	time	[s]
U	voltage	[v, mv]

Greek characters

ρ	rho	[Ωm]

Abbreviations

DT	Dwell Time
FT	Fall Time
HT	Hold Time
PHC	Pre Heat Current
PHT	Pre Heat Time
RT	Rise Time

ST	Squeeze Time
WC	Weld Current
WT	Weld Time

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1 Introduction

A significant amount of carbon dioxide is released into the atmosphere by a motor vehicle driven by diesel or petrol. To reduce carbon emissions and prevent the planet from climate change issues, Automakers are emphasizing the electric car in which a Li-ion battery pack is a power source. A battery pack comprises numerous separate cells that are joined together using various techniques. A battery pack is composed of myriad cells intricately arranged in a configuration that combines both series and parallel connections, all converging upon a central busbar. This connection between the cell tab and the busbar affected the overall performance of the battery pack and, ultimately, the electric car. So, the thesis aims to examine the electrical performance of bimetallic welded joints between the tab and busbar using resistance spot welding. The analysis commences by conducting an exhaustive review of existing literature of the various welding methods for joining a tab to a busbar in an electric vehicle battery pack. Next, this thesis will focus on Resistance spot Welding of Battery cell tab to busbar in which Nickle is used as a busbar material, and Ni-plated steel is used as a tab material—followed by Testing of electrical performance and microanalysis of the welded joint.

1.1 Background and motivation

Because of more utilization of fossil fuels in the transportation sector, it is liable for 24% of all worldwide carbon dioxide emissions. About 75% comes from vehicles with internal combustion engines (ICE). In response to this dangerous issue, carbon emission regulations have been established globally to lessen the negative consequences of climate change. (Sadeghian and Iqbal 2022, p. 1.)

These rules have compelled countries to upgrade the automobile industry and produce electric cars (EVs) to reduce their carbon impact. For instance, the UK intends to prohibit selling newer petrol and diesel vehicles starting in 2030 and Attain a state of carbon neutrality by the year 2050, effectively reducing greenhouse gas emissions to zero. (Sadeghian and Iqbal 2022, p. 3.)

Similar goals have been established by several powerful industrialized nations, including China and the EU. The European Union expressly declared the goal of 95 g CO2/km as the typical emissions for modern vehicle generation starting in 2020. The Chinese region of Hainan has outlawed purchasing fossil fuel vehicles as of March 1 and wants to switch to substitute propulsion systems by 2030 completely. A significant need for electric vehicles will emerge from the tendency to reduce the usage of fossil fuel automobiles, as electromobility is the best alternative propulsion. (Zwicker & Moghadam & Zhang & Nielsen 2020, p.2.)

Battery packs, constructed of multiple separate battery cells, store energy in electric cars. The effectiveness and efficiency of battery packs affect the range and speed of battery electric vehicles (BEVs). Lithium-ion batteries, specifically, have earned much recognition because they have the maximum energy density of all accessible technologies and are one crucial innovation that may decide the vehicle sector's life in the upcoming years. (Zwicker et al. 2020, p. 3.)

There are a variety of uses for lithium-ion batteries, including those found in portable electronics and electric vehicles. Lithium-ion batteries are a valuable source of power for electric cars (EVs) because they have a high energy density, low self-discharge rate, and are portable. Lithium-ion batteries also have a longer lifespan than nickel-cadmium batteries (HEVs or PHEVs). (Zwicker et al. 2020, pp. 4–5.)

Automobiles use three different kinds of battery cells. These include soft pouches or polymer cells, smaller solid cylindrical cells, and larger solid prismatic cells. Cells of various sizes and shapes are produced in existing vehicle lithium-ion battery production and arranged into packs of different combinations. A large variety of battery cells, frequently hundreds or even thousands, are combined to make battery packs to meet the appropriate power and capacity requirements. These battery cells are generally attached in series and parallel to form a module. Series connections enhance the power supply, while parallel connections secure the highest capacity. battery pack is made up of several dozen modules as shown in figure 1. (Zwicker et al. 2020, pp. 5–7.)

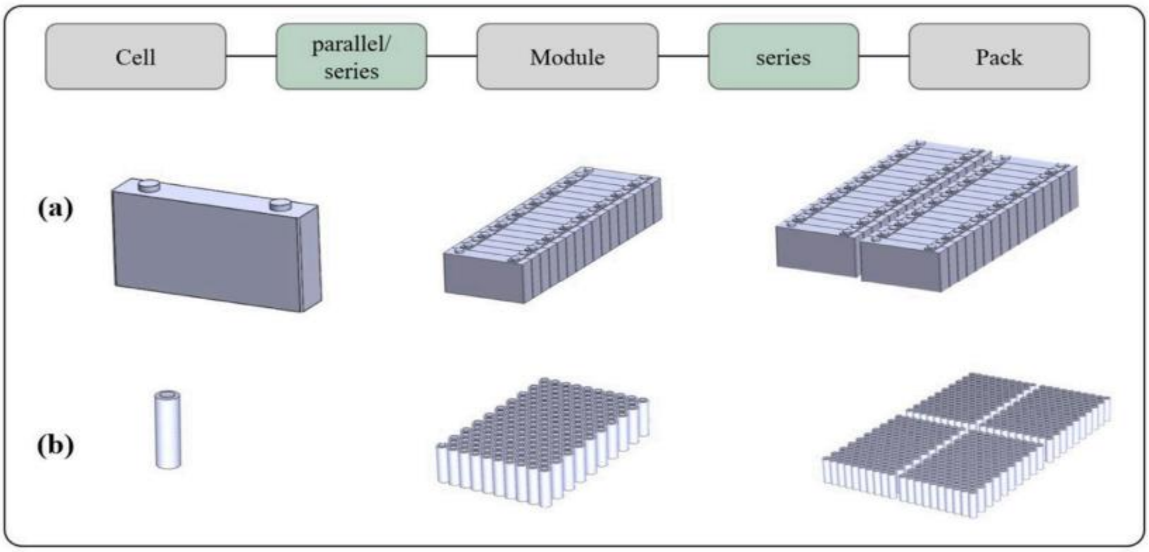

Figure 1. The EV Battery pack overview with (a) prismatic cells (b) cylindrical cells (Sadeghian and Iqbal 2022, p. 2).

The various cell types depicted in the following figure 2 are commonly utilized in battery packs.

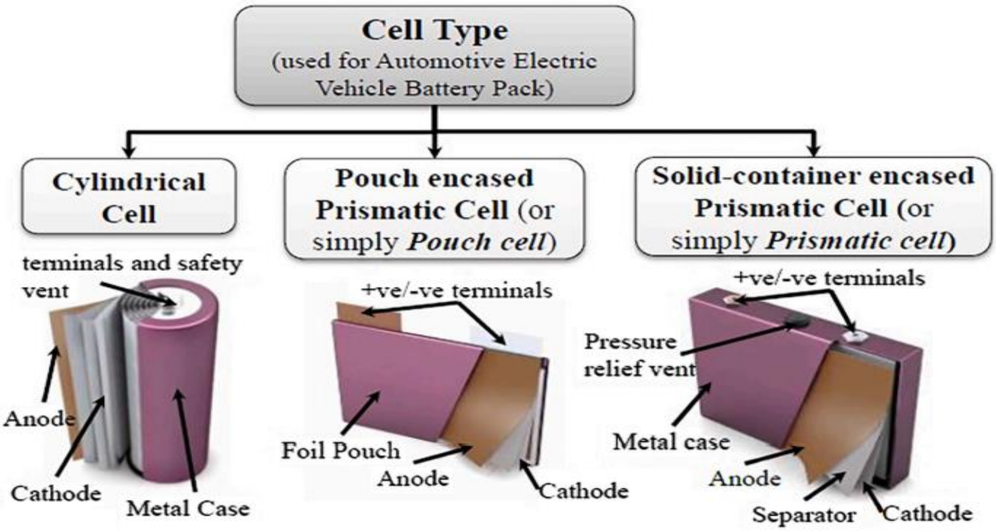

Figure 2. Cell Types 1) cylindrical cell 2) pouch cell 3) Prismatic cell (Sadeghian and Iqbal 2022, p. 3).

Producers of battery packs typically buy individual batteries from suppliers. As represent in the figure 3, The crucial procedure phase for Battery pack production is to join the individual cell tab to the busbar. The busbar connects both ends of the battery cell (positive and negative). The function of the busbar is to conduct and transfer the electricity along the battery pack from each cell. (Schmidt, Schweier and Zaeh 2012, p. 2.)

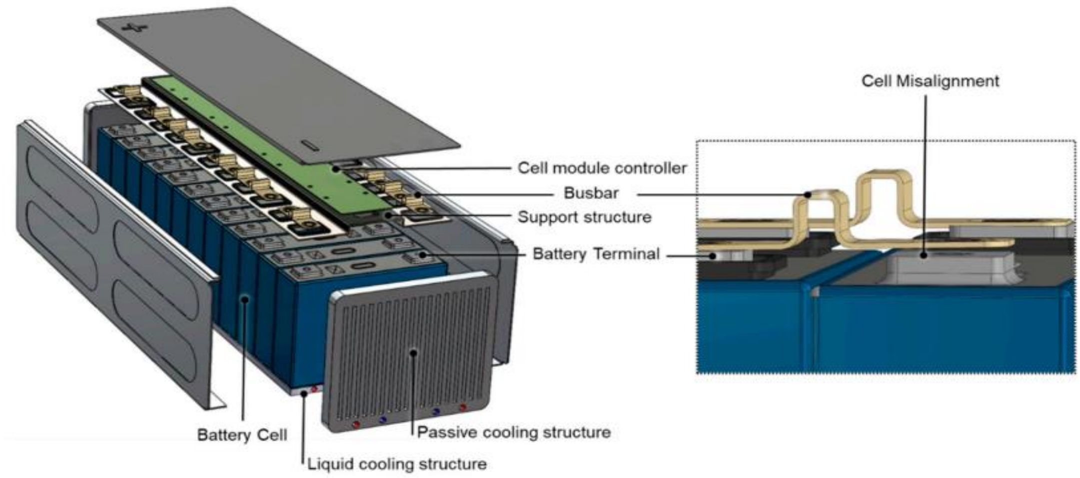

Figure 3. Detailed view of battery-pack (Saariluoma and Piiroinen and Unt and Hakanen 2020, pp.3).

Moreover, automobile batteries are subjected to severe driving conditions such as vibration, extreme temperatures, and collisions, which may reduce their efficiency. In addition, hundreds of thousands of battery packs will be manufactured each year for car quantity manufacturing. Hence, battery assembly requires reliable joining procedures, Hence effective joining techniques are increasingly important. (Zwicker et al. 2020, pp. 5–6.)

So, choosing a proper joining technology is necessary for battery pack manufacturing as Chosen welding technology significantly impacts battery-pack efficiency and the overall efficiency of the electric vehicle.

An appropriate electric vehicle battery system Cell tab to Busbar joint must meet the following criteria.

• Low electrical resistance

• Good strength

• High fatigue resistance

• Low corrosion risk (Sadeghian and Iqbal 2022, pp. 3–4.)

1.2 Objectives and research questions

The sphere of this research is to improve the efficiency of the Electric vehicle battery pack by improving the electrical properties by reducing the resistance of the welded joint between the cell tab and busbar using resistance spot welding. Furthermore, the study investigates how resistance spot welding can be utilized to weld dissimilar materials (Ni to Ni-plated steel) with a thickness of 0.5 mm. Figure 4 illustrates the central objective of the thesis.

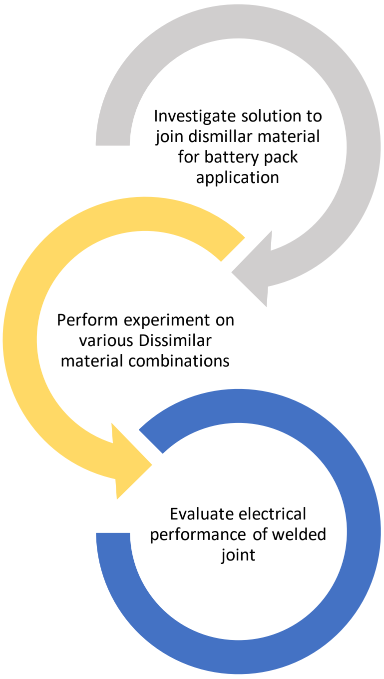

Figure 4. Aim of Thesis.

Objectives:

The research aims to investigate the electrical performance of dissimilar bimetallic material welded joints between the tab to busbar for an electric car battery pack application. The objective to be discussed from the experiment perspective are:

- Find out weldability of different dissimilar material combinations by performing initial experiments using resistance spot welding.
- Analyse reliable and effective material combination.
- Perform experiment, identify process parameters, and generate weld.
- Evaluate electrical performance of welded joints.
- Perform Microanalysis of welded joint

To analyse, discuss, and interpret results achieved from welding of two dissimilar material.

Research questions:

1. How can the electrical performance of the welded joint between battery cell to tab improved?
2. Which is the best welding method to join dissimilar material in battery pack application?
3. What are the best weldable material combinations for resistance spot welding in battery pack application?
4. How can we join thicker material using resistance spot welding?
5. What are the effective parameters to Join dissimilar material like Nickel-to-Nickel plated steel using Resistance spot welding?

1.3 Methodology

The procedures used to compile this report will be arranged as shown in figure 5. Although the main goal of thesis is to investigate the electrical performance of the welded joint between the cell tab and busbar, thesis explored different dissimilar material combinations to check their weldability and for that initial experiments are performed first. In doing so, weldable material combinations will be identified and further proceed to electrical properties measurement especially electrical resistance. In chapter 5, the measured electrical resistance of the welded joint between the Nickel-to-Nickel plated steel is described. The conclusion also outlines the key findings of the study and Figure 5 presents the approach in graphical format.

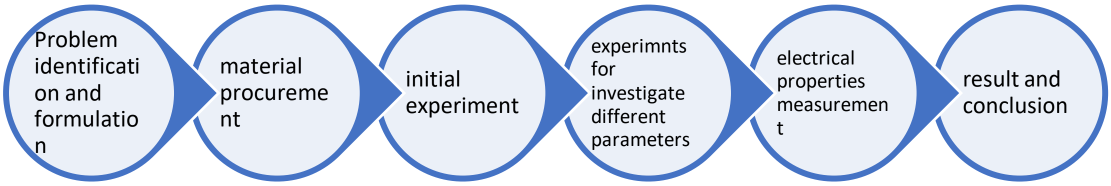

Figure 5. Methodology.

1.4 Layout of Thesis

The thesis work started with a basic introduction about the battery pack and some background information related to the research topic. Later in chapter 2 critical literature review started with the challenges of joining dissimilar materials in battery-pack applications, followed by various solution and welding technologies to join dissimilar materials. In chapter 3, the base material used in the experiment is broadly described. Experimental methodology and testing and characterizing welded samples are also part of chapter 3. The last chapter Result section discusses process parameters and measured connection resistance. Thesis ends with a practical discussion.

2 Literature Review

New Methods or concept demands research into previous approaches and studies on the topic. The results of earlier research can be utilized to create novel approaches and expand the areas of research and experiment. Literature reviews focus on the challenges of dissimilar materials and existing solutions of it in battery pack production.

2.1 Challenges of dissimilar material welding for battery-pack manufacturing

To join dissimilar materials is very challenging. In battery-pack production, dissimilar materials are often used. In the battery pack, when two dissimilar materials are joined, due to their different thermal expansion, heat is sometimes produced around the weld region, resulting in shear loading and sometimes severe fracture in the welded joint and plastic deformation. These resulting phenomena, plastic deformation and shear loading adversely affected the welded joint's resistance and the battery pack's overall efficiency. (Zwicker et al. 2020, pp. 6–8.)

In dissimilar materials joints, both materials have different properties, like melting temperature and thermal conductivity. Because of that, it is challenging to join the two dissimilar materials as they do not create a metallurgical bond. Lacking metallurgical bonds can create cracks and porosities in the welded joint. In the harsh driving conditions, dynamic loading, vibrations, and possible crashes, a poor joint could even cause a fire if a short circuit formed. (Matthias and Oliver and Michael and Bernard 2011, pp. 4769.)

While joining two dissimilar materials, an intermetallic layer form. Which makes the joint more brittle than the parent material; the intermetallic layer is a significant contributor to the higher resistance of the connection. The development of intermetallic layers raises the probability of a corrosion risk, which, in turn, will diminish the electro-mechanical efficiency of the welded joints. (Wang et al. 2016, pp. 3081–3083 ; Lee et al. 2016, pp. 3-5.)

In the battery pack, cells are subjected to charging and discharging. During that time, the intermetallic layer's presence can increase heat production due to its low electrical conductivity, ultimately enhancing the degradation process of the battery. (Trinh and Lee 2020, pp. 2–3.)

In Summary, the primary joint qualities that need to be satisfied for the connections between the battery tab and busbar are low electrical resistance and good mechanical strength. It is essential to meet these requirements. A poorly made joint could cause a more significant electrical resistance, which would result in an excessive amount of Joule heating. (Bao and Zhao 2018, pp. 79–81.)

2.2 Solution of dissimilar material welding for battery-pack manufacturing

Various joining technologies are used in battery-pack production to join dissimilar materials. Laser welding, ultrasonic welding, Resistance spot welding, and micro Tig welding are standard methods for joining dissimilar cell tabs to busbar terminals. Each technique has its benefits and drawbacks and is deployed differently depending on the cell type, material qualities, and thickness. Presented below are technologies that have been reviewed in scientific literature for their potential use in battery-joining applications.

2.2.1 Laser welding:

Laser welding’s high-power density and low energy input make it ideal for joining dissimilar materials, but its use necessitates a systematic approach. For fast, repetitive, high-quality welding of components, a concentrated CO2 laser beam has several benefits over traditional joining procedures because of its high-power density. The automotive sector has widely adopted laser welding as a conventional approach for combining various dissimilar metals. (Karppi 1996, pp. 257–258.)

Real-time system monitoring has made laser welding the best technique for joining materials. Laser welding is frequently used in sizeable serial production because of its minimal heat input, rapid functioning, the convenience of automation, and repeatability. Laser welding's non-contact nature, rapid throughput, ability to join dissimilar metals, and versatility in weld design implementation make it the perfect technique for battery packs. Lap joint, fillet joint, and laser spot welding are the three configurations employed when welding busbars to battery cell terminals. (Saariluoma and Piiroinen and Unt and Hakanen 2020, pp. 4-5.)

The most common welding techniques utilized for prismatic, pouch, and cylindrical cell types are laser spot welding with lap joint. Fillet joints are utilized in situations where the terminal connector busbar structure includes a gap. (Saariluoma et al. 2020, pp. 4–5.)

With the advent of new laser sources like single-mode fibre lasers and nanosecond pulses, dissimilar metal welding has the potential to significantly increase battery efficiency by lowering electrical resistance. The method has been proven effective in generating good pull and peel strengths in these dissimilar joints with metals thinner than 0.25 mm. This cutting-edge innovation has broad applicability, resulting in positive outcomes for many industries. (Alexy and van de Wall and Shannon and Boyle 2019, pp. 53-56.)

Fast cycle times are a fundamental advantage of laser welding, allowing manufacturers to produce more than they could use resistance welding; Additionally, laser welding is a method that excludes any physical contact. No electrodes come into contact with that part due to the very few chances of polluting the surface. This has some positive aspects but also some negative ones to consider. Quality control is complicated in laser welding compared to resistance welding, as it is difficult to monitor. Laser welding also fails to measure up to resistance welding when it comes to the ability to supervise the welding process. (Alexy et al. 2019, p. 57.) below Figure 6 shows strips of metal that are welded to cylindrical battery cells to make connections.

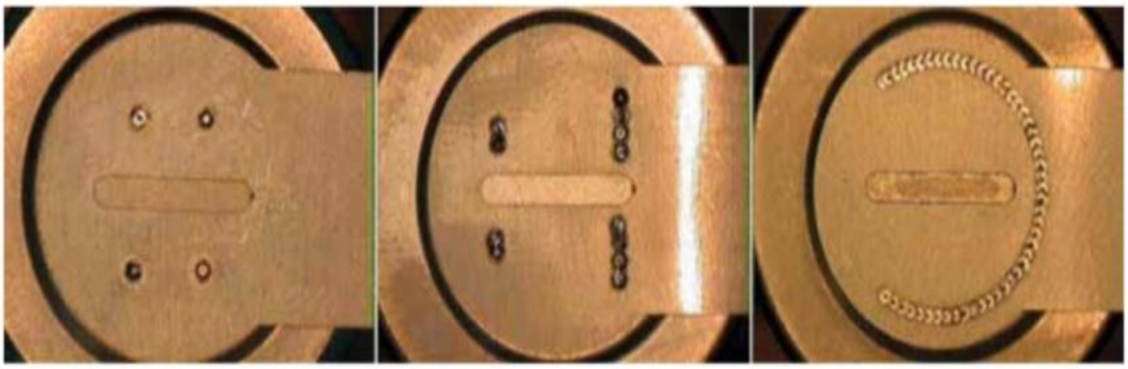

Figure 6. Application of laser welding- cylindrical cell to Busbar connection (Zwicker et al. 2020, p. 9).

(Schmidt, Pauleser and Zaeh, 2014) and (Brand, Schmidt and Zaeh and Jossen, 2015) found that the weld seam arrangement's area, shape, and size directly influenced connection resistance. Additionally, according to (Brand et al., 2015), when particularly in comparison to resistance and ultrasonic welding, laser welding has the lowest connection resistance when laser parameters are optimized, there is little heat input.

In their study, (Shaikh, Das and Barai and Masters, 2019) delved into the electro-thermo-mechanical performance of copper laser-welded to nickel-plated steel. According to (Shaikh et al., 2019), the joint's resistance was only slightly higher than that of the metal to which it was joined. Metallurgical behaviours of the two materials were considered the root cause of joint resistance increasing with joint strength.

When exploring the effect of various pulsed laser techniques on the resulting connection resistance, (Schmitz, 2016) used a setup like that of (Brand et al., 2015). His research contradicts the findings of preceding authors by showing that the resistance of electrical connections has no bearing on the overall joint area.

2.2.2 Ultrasonic welding

Ultrasonic wave energy is the foundation of its operation. The ultrasonic welding process requires a sonotrode, a machine that produces ultrasonic vibrations. The sonotrode comprises a series of piezoelectric transducers fitted on a shrinking metallic rod. When the sonotrode starts to vibrate, heat is produced between two workpieces; this generated heat will eventually form a weld.

Ultrasonic welding is preferable to other methods for welding highly conductive dissimilar metals together because it produces strong welds free of porosity, hot cracks, and bulk intermetallic. Ultrasonic welding is most likely to cause component damage through vibration. The ultrasonic welding process is very sensitive to contamination. Even a tiny amount of contamination, like the grease from a fingertip, can entirely disrupt the process. Additionally, ultrasonic welding produces more significant heat compared to other methods, which might harm batteries. (Alexy et al. 2019, p. 61.)

The real benefit of ultrasonic welding is that it is effective when combining several sheets and dissimilar materials, which is essential for both cell and battery tab welding. Because of its low operating temperature and relatively high efficiency when working with aluminium, copper, and other materials, ultrasonic welding is a technique that is frequently used in the production of batteries. Since ultrasonic metal welding does not use gases or filler metals, it is eco-friendly.(Lee, Kim and Hu 2016, p. 3.)

However, employing ultrasonic welding for metal does have a few downsides, one of which is a limitation on the joint thickness (3mm), susceptibility to product/process variables like surface conditions, and difficulties attaching materials with high strength. However, since ultrasonic welding has strong weldability for connecting dissimilar and many thin layers, it is considered preferable to other welding techniques, particularly for connecting pouch-type prismatic battery cells. (Lee et al. 2016, pp. 3-4.)

It uses ultrasonic vibrations of a high frequency, typically 20 kHz or above, can cause significant vibration, compromising the structure's integrity and making it unsuitable for cylindrical and prismatic cells. (Das, Li, and Williams, 2018)

Among many other techniques, (Brand et al., 2015) used ultrasonic welding to join cylindrical battery cells. The welded joint resistance was evaluated, and a relationship was discovered between the weld area and the resulting resistance where the weld area is inversely proportional to the joint resistance further; it was also noted that ultrasonic welding generates significantly more heat than laser welding or resistance welding.

The electrical and thermal properties of ultrasonic joints were studied with the current flow by (Das, Barai and Masters, 2019). The connections between the joints became more resistant as their temperatures rose.

(Nalajam, 2018) examined the connection resistance of copper and aluminium wires with various processing parameters while considering intermetallic compounds.

2.2.3 Micro TIG or Pulsed arc welding

Micro Tig welding is an emerging joining procedure for battery pack production. Instead of using filler wire, this welding method uses a pulsed arc to join the material, producing much concentrated localized heat. The Micro TIG method is used to join the dissimilar material as the arc pulse has a concise duration, measured in microseconds; as a result, the heat input is significantly lower than in traditional TIG welding. Micro TIG welding is performed without touching the metal. Controlling the current is essential since the amount of heat created by micro TIG welding directly depends on the current and resistance of the arc. (Alexy et al. 2019, pp. 61–62; Das et al. 2018, p. 4.) figure 7 illustrated the Cylindrical cell tab to busbar joining by pulsed arc welding.

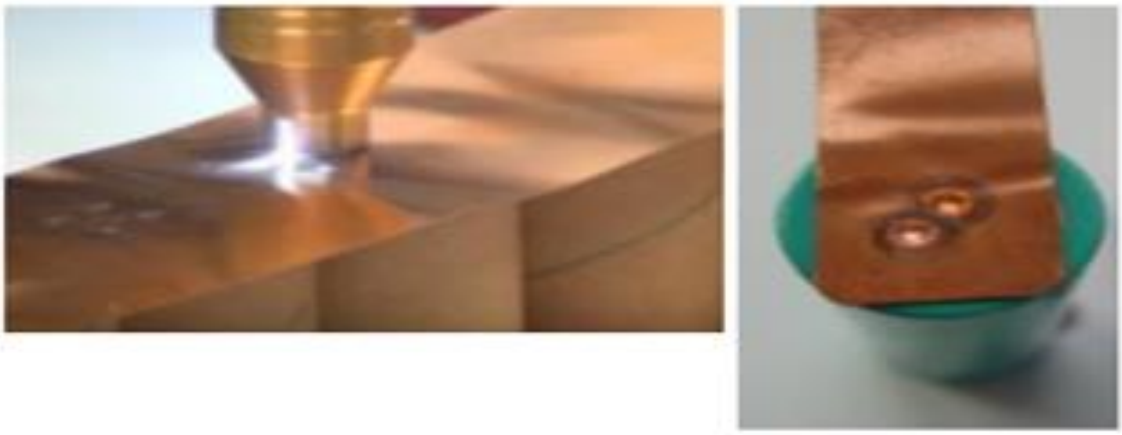

Figure 7. Cylindrical cell tab to busbar joining by pulsed arc welding (Das et al. 2018, p. 5).

In the production of Battery-pack, pulsed arc welding is utilized to attach the cell tab to the busbar. Typically, pulsed arc welding welds tab and Busbar materials such as nickel and copper. Pulsed arc welding is difficult to perform on dissimilar conductive materials, such as aluminium and copper. It can be seen in the figure 8, Similar materials, such as copper tab and busbar, can be welded using the pulsed arc welding technique. (Das et al. 2018, pp. 5-6.)

Studies on Micro TIG welding in industries have yet to be available. on the other hand, (Das et al., 2019) examined the weldability and electro-mechanical performance of an aluminium-to-nickel-plated-copper welded joint using Micro TIG welding.

When welding battery packs, the micro TIG process has one major drawback: the significant heat-affected zone it creates. The tungsten electrodes become dull over time and must be sharpened and cleaned periodically. (Alexy et al. 2019, p. 64.)

2.2.4 Ultrasonic wedge bonding

As shown in the figure 8, ultrasonic wedge bonding involves feeding a small wire made from conductive materials like (copper and Aluminium) through the weld head in the opposite direction of the busbar in most cases, an atomic bond between the two surfaces is what causes an ultrasonic wedge welding joint to form. An ultrasonic wedge bond primarily functions as a cleaning and mating process to clean and mate surfaces to a specific distance where they will create an atomic bond. Mechanical interlocking is one method that significantly contributes to the joining process. A bonded wire could be used for a switching operation to protect the battery pack from extreme mechanical conditions and internal defects. The ultrasonic wedge bonding technique is an optional welding method to weld dissimilar materials. The cells and bus bar within the battery module must be rigidly fixed to implement the technology. Adhesives or glue are often necessary to give cells greater rigidity. (Das et al. 2018, p. 4.)

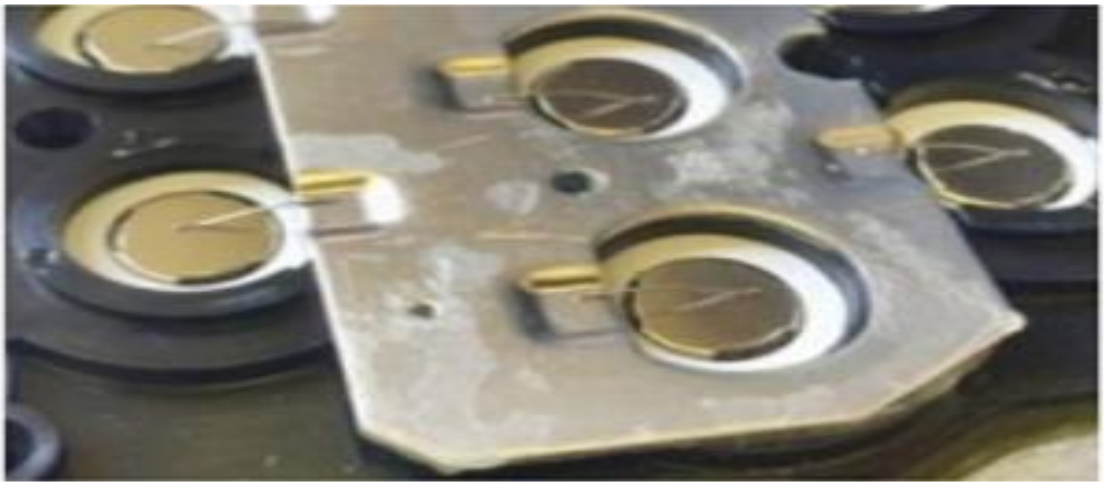

Figure 8. Ultrasonic wedge bonding for cylindrical cell application (Das et al. 2018, p. 5)

2.3 Resistance spot welding for dissimilar material welding for battery-pack manufacturing

Resistance welding is a fusion welding process which obeys the Joule's law.

Below equation 1 states Joule's law

$$H= I^2RT \tag{1}$$

Where, H= amount of generated heat during the welding process

I= welding current

R= resistance of the intermetallic joint

t = welding time

Resistance spot welding, as depicted in below figure 9, uses two copper dome-shaped electrodes. Welding current can be more precisely directed with dome-shaped electrodes. Using two electrodes and applying pressure, materials can be joined together. During this process, two electrodes pass a high current at the same time. With enough current flowing between the electrodes, the metal surfaces will melt, creating a weld. Resistance spot welding often involves focusing much energy on a tiny area for a brief period (10–100ms). Due to the shorter time, welding can be performed without causing excessive heat. Resistance spot welding requires the right energy to achieve a high-quality weld. Because insufficient energy will fail to melt the metal, resulting in a weak weld, and excessive energy will cause the metal to melt too much, creating a void in the welded area. (Das Tanmoy, 2022)

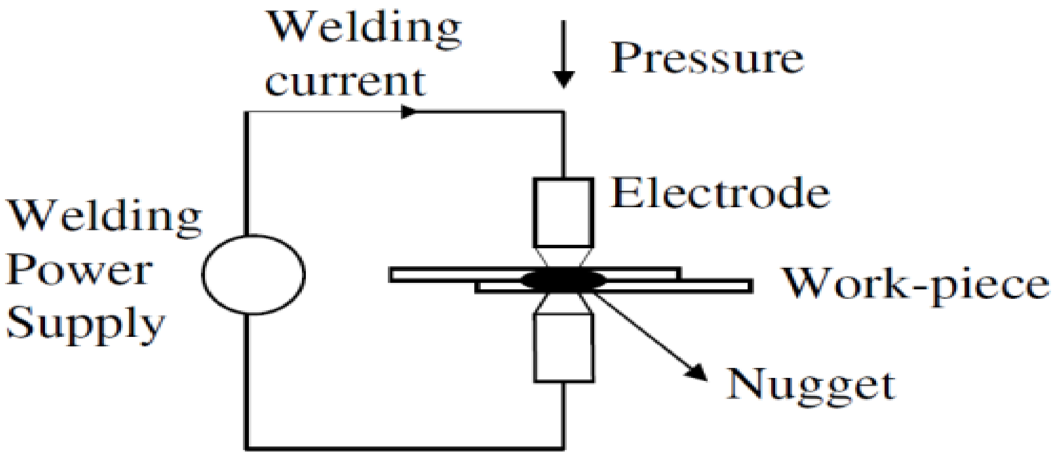

Figure 9. schematic diagram of resistance spot welding (Jahandideh and Hamedi and Mansourzadeh 2010, p. 1).

- Resistance spot welding for battery pack manufacturing

Resistance spot welding is a quick and easy-to-control technique. This reliable technique has been used for a long time and needs a small investment. As shown in figure 10, In Resistance spot welding, users can generate a weld manually by pressing the foot paddle, which directly controls the weld head.   Now in recent times, weld heads operate automatically.

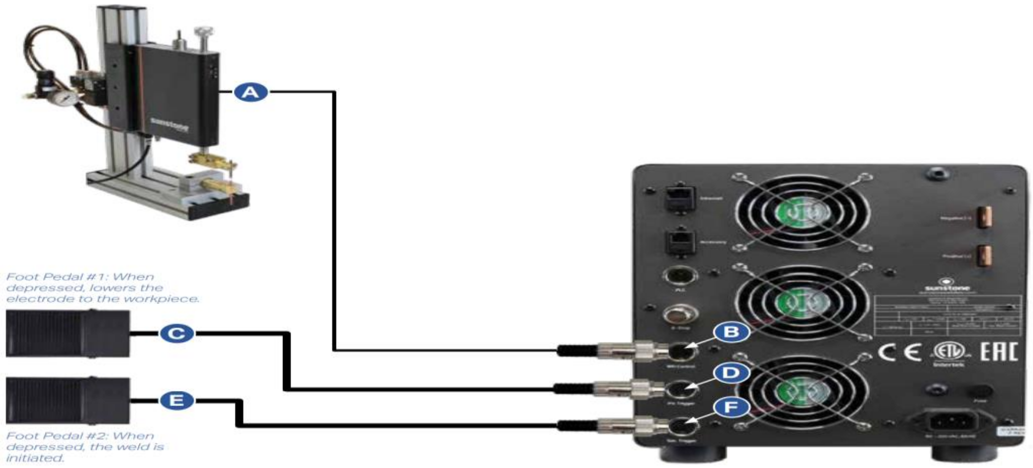

Figure 10. SUNSTONE CDDP-A resistance spot welding machine (SUNSTONE CDDP-A manual, LUT JHC)

During the battery tab to busbar welding, process equipment can easily measure the electrical and mechanical properties like the voltage, resistance, power, force, welding speed, movement of electrodes, etc. (Alexy et al. 2019, p. 57.)

During resistance spot welding, the welded workpiece must be touched. Easy data tracking and management are possible in Resistance spot welding. However, RSW presents difficulties like electrode sticking once it is imposed on battery welding. Similarly conductive materials, dissimilar materials possessing various melting points, and the smaller weld nugget undergoing heat formation all through charging-discharging due to the rising current density.(Das et al. 2018, p. 3 ; Alexy et al. 2019, p.57.)

Lithium-ion battery electrodes and tabs are often comprised of highly conductive materials such as aluminium and copper, which are not suitable for resistance welding. nickel is a resistive material; nickel plating coating improves the weldability of conductive materials. Nickel and HILUMIN, an electro nickel-plated steel strip, have historically been employed in battery technologies. Metals like copper and aluminium are good electrical conductors and have low electrical resistance and have been increasingly used in recent years. To produce a battery pack with greater efficiency, thicker materials are also being employed. This is because thicker materials have lower resistance and permit more current flow. (Alexy et al. 2019, p. 58-59; Lee et al. 2016, p.4.) The most often used materials for battery tabs, aluminium, copper, and nickel, are summarized simply in TABLE 1 below for their weldability.

Table 1. weldability of different dissimilar conductive material combination (Lee et al. 2016, p.5).

Material with melting point	Aluminium (660 ℃)	Copper (1080 ℃)	Nickle (1450 ℃)
Aluminium (660 ℃)	Electrode sticking	-difficult -low joint strength -electrode sticking	- difficult - low joint strength
Copper (1080 ℃)	-	-Good	- low joint strength
Nickle (1450 ℃)	-	-	- excellent

Two primary strategies can be utilized during the welding operation of a battery tab. In the initial alternative seen in fig 11 left side, the welding electrode makes direct contact with the tab that needs to be joined, while the connecting electrode interacts with the edge of the battery pole.

The other approach, which can be seen in figure 11 (right side), involves two welding electrodes encountering the tab, which necessitates the adoption of a slotted design for the tab to create a defined welding current route through the tab and to improve the strength of the weld.

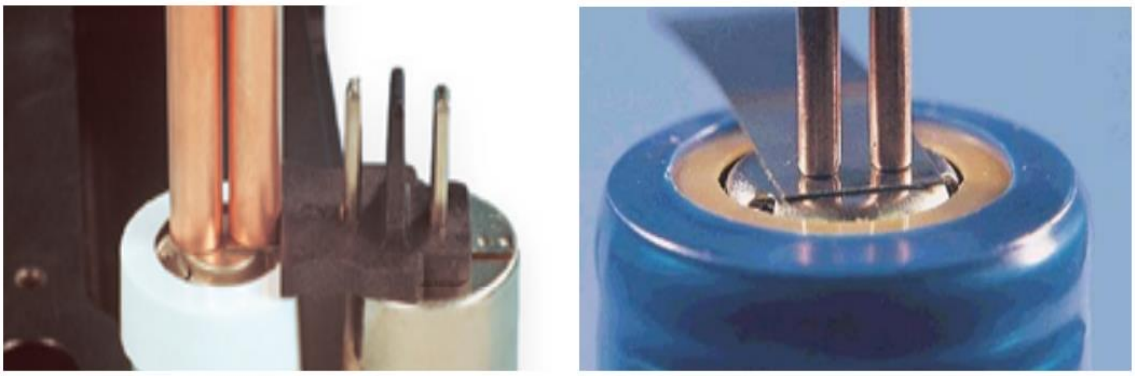

Figure 11. Application of approaches in the resistance spot battery tab welding (Alexy et al. 2019, p. 4).

Li-Ion battery cells can be welded by resistance spot welding, as shown in the below figure 12.

Figure 12. Battery pack resistance spot welding(Alexy et al. 2019, p. 5).

(Brand et al., 2015) evaluated the contact resistance between the cell tab and busbar using resistance spot weld; in his research, he emphasized using high resistive material for spot welding. They also evaluated that contact resistance is lower when weld spots are increased.

According to (Godek and Godek, 2013) research, weld width and connection resistance decreased as energy input rose. Additional research was done by (Masomtob, Sukondhasingha and Becker, 2017) and (Martinez and Lostado, 2015) but neither of the essential variables, such as connection resistance or heat input, were examined.

(Phichai, Kaewtatip and Lailuck, 2019) investigated how resistance spot welding parameters affect the welds between battery cells and Hilumin/Nickel strips. They concluded that slots on the joining tab could increase the electric current that passes via the nuggets. That nickel tab is a better material choice for the connection tab over helium at a similar level of peak supplied voltage. On the other hand, the processing parameters needed to be improved to obtain a low connection resistance.

(Kumar, Ramakrishnan and Panchapakesan, 2022) was worked on to optimize process parameters for Nickle to Hilumin (cell tab to busbar) welding for battery-pack application. In research, they found optimal process parameters for the welding and evaluated the connection resistance and temperature rise phenomena.

According to (Ely and Zhou, 2001) Nickel is somewhat tricky to micro-resistance weld since it exhibits enhanced electrode-sticking and demands a more significant welding current or pulse energy. In a different investigation by (Kumar et al., 2022), ultra-thin Inconel was joined to stainless steel using micro resistance spot welding. The researchers found that the welding current and time significantly affected the joint's electro-mechanical properties.

- Advantages and limitations of various welding techniques used for the battery-pack application.

several welding techniques are being used for the battery pack welding especially tab to busbar. Many techniques have their advantages and limitations which are mentioned in below table 2.

Table 2. Battery pack welding technology with their advantage and limit

Sr.no	Welding Process	Advantage	Disadvantage
1	Laser Welding	• High speed • Low thermal input • Easy automation • Non-contact process	• High initial cost • Hard to produce large joint area. • Material reflectivity
2	Ultrasonic welding	• Solid state processes • No filler metal or gases • Excellent for highly conductive materials	• Restricted to lap joint. • Sensitive to surface condition • Sonotrode sticking. • Limited in joint thickness

Table 2 continues. Battery pack welding technology with their advantage and limit

3	Resistance welding	• Efficient and low coast • Fully automated • No filler metals or gases • Good quality control	• Difficult for highly conductive and dissimilar material • Electrode sticking • Difficult to produce large nugget. • Possible expulsions
4	Micro TIG welding	• Multiple head from one unit • Able to weld plated material. • Low cost • High joint strength • Able to join dissimilar material	• High thermal input and heat affected zone. • Porosity

2.4 Research Gap and justification for objective

The foremost things that must be true about the connection between the battery tab and the cell terminal are low electrical resistance and excellent mechanical strength. If the connections are not made right, the electrical resistance could go up, which would cause too much Joule heating.

Although there are many welding techniques for cell tab joining, The goal is to select inexpensive joining procedures while also meeting the requirements for combining different types of dissimilar materials. Due to its low capital investment requirements and low trained labour requirements, RSW is one of the best welding techniques when considering the abovementioned requirements. Hence The current work uses the micro-RSW methodology to join cell tab to busbar, which are commonly used in portable electronics and automotive applications. This is because it has a low initial capital expenditure, a quick processing time, low electrical contact resistance, and good corrosion resistance.

As we have seen in the literature review, (Brand et al., 2015 ; (Alexy *et al.*, 2019) found that nickel is a suitable material for battery tab welding as it is less conductive. According to (Godek and Godek, 2013) research, weld width and connection resistance decreased as energy input rose. Additional research was done by (Masomtob et al.,2017) and (Martinez et al.,2015) but neither of the essential variables, such as connection resistance or heat input, were examined.

(Phichai et al., 2019) investigated how resistance spot welding parameters affect the welds between battery cells and Hilumin/Nickel strips. They concluded that slots on the joining tab could increase the electric current that passes via the nuggets. That nickel tab is a better material choice for the connection tab over helium at a similar level of peak supplied voltage. On the other hand, the processing parameters needed to be improved to obtain a low connection resistance. In his research (Alexy et al., 2019) still assumed future possibilities on reducing cell tabs to busbar contact resistance.

However (Kumar et al., 2022) worked on optimizing resistance spot welding parameters to reduce the connection resistance but they selected thin materials (0.2mm nickle to 0.4mm Hilumin). (Lee et al., 2016) suggest using thicker material for battery pack joining because thicker materials have lower resistance and permit more current flow, and eventually improve the electrical efficiency of the battery pack.

Reading the research on battery joining, it is evident that electrical characterization of joints, especially joint resistance, is only sometimes performed. It is accomplished through several papers, whereas the scientific studies, the applied procedures, and the outcomes differ substantially from one another. There is also clear evidence of differences in the analysed parameters.

Within the scope of the literature review, resistance spot welding joining of 0.5 mm Ni-plated steel connecting tabs to Nickel battery cell terminals inside a battery pack has yet to be extensively investigated. For micro-RSW joints, a thorough investigation of electrical contact resistance is required.

So according to past research, it is still possibility to reduce connection resistance in the resistance spot welding by using thicker material. Reduction of Connection resistance will improve the overall electrical performance of battery pack and will help to achieve a sustainable zero carbon emission goal.

3 Materials and Methodology

In the realm of research, a variety of base materials are employed in conjunction with a specific methodology. In resistance spot welding, the selection of appropriate base materials and the adherence to a well-defined methodology are paramount factors contributing to the quality of the weld.

3.1 Base Material

To reduce power losses and increase heat dissipation, the materials used for battery tabs should be highly conductive. Nickel, copper, electrical-grade steel, and aluminium are all viable options for the battery tab due to their high electrical and thermal conductivity. Price, suitability with cell terminal materials, corrosion resistance, welding procedure, and good tensile and fatigue qualities are also considered when deciding on a material for the battery tab.

In the Battery-pack manufacturing many similar and dissimilar material are used but Steel and nickel's high electrical resistance and low thermal conductivity make them ideal for resistance spot welding. In general, Nickel is a suitable material for resistance spot welding, as it is 12 times more conductive than stainless steel and can take high current loads without voltage drop. Compared to conducting materials like copper and aluminium, nickel is more resistant.

High resistivity material is necessary for successful resistance spot welding to produce a good weld. In contrast to more conductive materials, nickel may be easier to spot weld due to its high resistivity and low melting point. So, in this Research Ni and Ni-plated steel (Hilumin) were chosen as an Experimental material as described in Table 3 below.

Table 3. Materials used during the experiments

Sr. No	Material	Thickness
1	Hilumin (NI-plated steel)	0.5mm / 0.6 µm nickel layer
2	Nickle	0.1mm

3.2 Experimental Set up

The Research aims to join the NI-plated steel tab to the Nickel terminal. In this Research, the experimental material 0.5mm thick Ni-plated steel (Hilumin) and 0.1mm Ni strip with dimensions of 35mm×10mm and 35mm×10mm was chosen. Experiments were carried out in a lap joint configuration to join 0.5mm Hilumin (NI-plated steel) and 0.1mm Ni strips as illustrated in figure 13. Distance between the workpiece and electrode was 0.125".

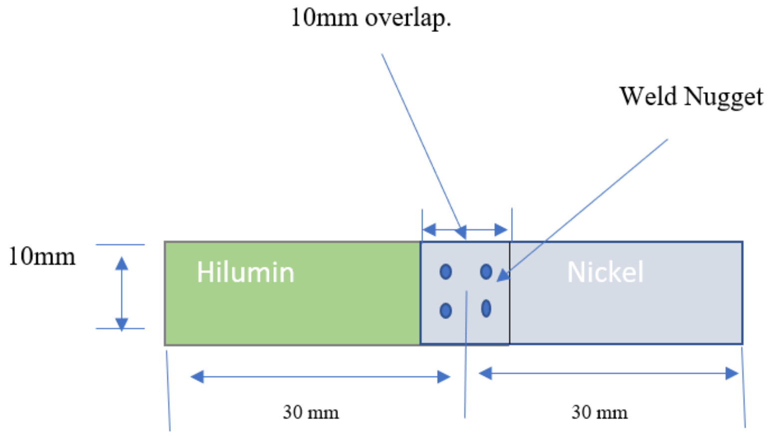

Figure 13. schematic diagram of 0.1 mm Nickle and 0.5mm Ni-plated steel overlap resistance spot welding configuration

As shown in figure 14 Resistance spot welding was performed on a Sunstone CDDP-A welding machine with a 10000-amp output current flow. As copper has excellent electrical conductivity, Copper electrodes with a dome-like shape and 1.6 millimetres in diameter were used. Generally, in Resistance spot welding, Flat and dome-shaped electrode is used. When comparing the two types of electrodes, the dome-shaped electrode has a longer life than the flat electrode. (Phichai et al., 2019)

Figure 14. Experimental setup and Sunstone resistance spot welding machine

The below figure 15 depicts the parallel electrode setup utilized during the experiment. Electrode pressure is just one of many parameters that significantly affect the success of a spot weld. It is crucial to ensure an ideal pressure to achieve good weld strength, as higher pressures on the electrodes lead to lower contact resistance and cooler welds. In comparison, lower pressures led to hotter welds and higher contact resistances.

As illustrated in the figure 15, the optimal pressure was applied on both electrodes, and due to the higher contact resistance of the nickel strip, heat is produced. Metal starts to melt, and eventually, the weld is created.

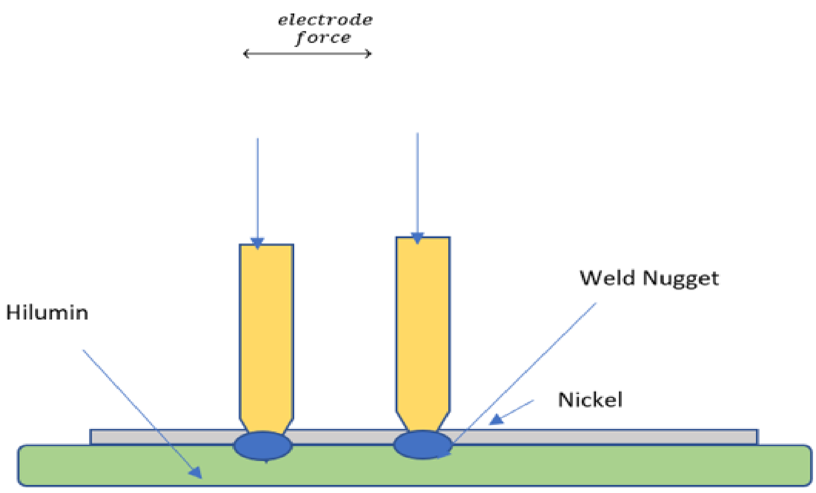

Figure 15. current flow while resistance spot welding

3.3 Experimental Methodology

Appropriate mythology plays a crucial role in achieving desired results in any research. This research follows a systematic experimental approach, which is listed below in figure 16 step by step.

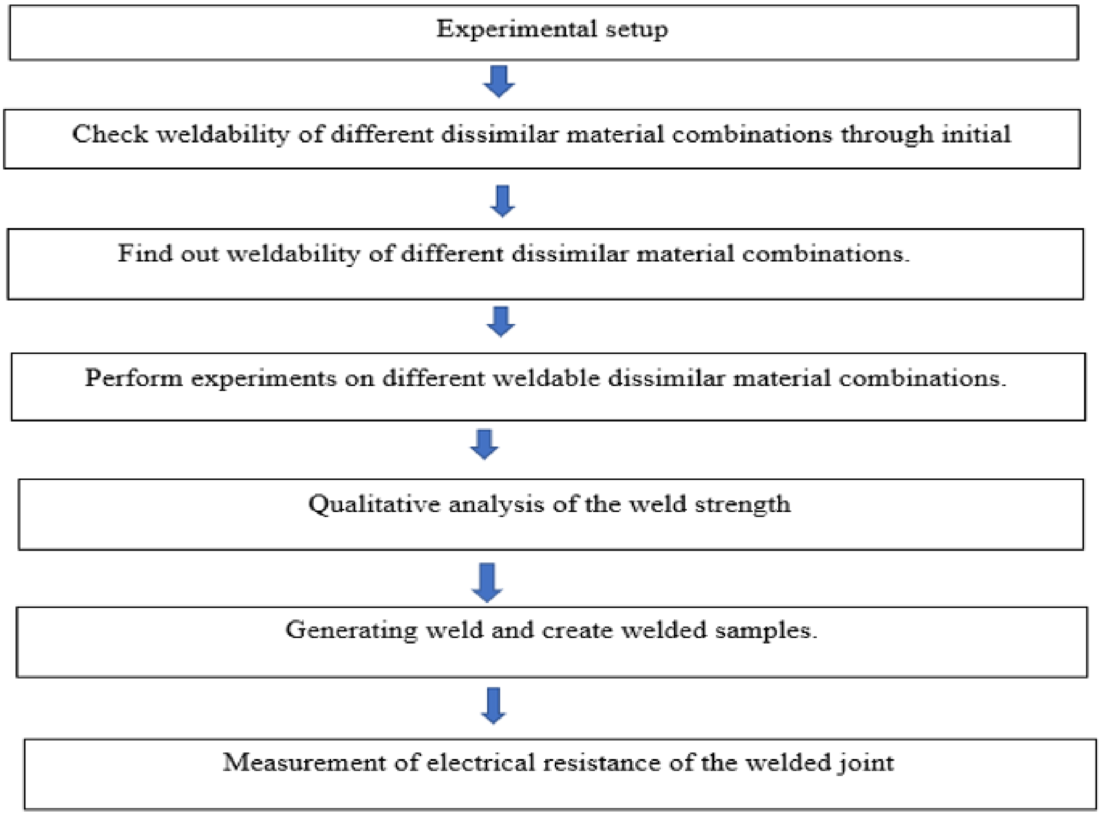

Figure 16 Experimental methodology

3.3.1 Electrode sticking test

Resistance spot welding's electrode sticking phenomenon was analysed by (Dong, Kelkar, & Zhou, 2002) in terms of influencing parameters. They concluded that many factors, including welding current, welding time, and electrode force, all have a role in electrode sticking. They observed that the metallurgical link between the electrode and the nickel-plated steel was to blame for this effect when they performed micro resistance spot welding on both materials. Applying more pressure to the electrodes can solve the problem of electrode sticking.

In this Research, electrode sticking test was conducted on the workpiece; in this test, electrode force varied between 7 lbs/one electrode to 15 lbs/one electrode. During this period, it was observed that electrodes were sticking on the workpiece at low pressure of electrode and generating excessive heat, and eventually burning the workpiece. During the test, it was observed that an electrode was not sticking to the workpiece material at the highest pressure of 12 lbs / one electrode. Experiments were conducted on the maximum pressure in this research. Table 4 describe different electrode force of sunstone CDDPA welding machine.

Table 4. Electrode force sunstone CDDPA welding machine

Spring force marker	lbs/one electrode	Kg/one electrode
4	7	3.2
5	9	4.1
6	11	5
7	13	5.9
8	15	6.8

According to (Ely and Zhou, 2001) Nickel is somewhat tricky to micro-resistance weld since it exhibits enhanced electrode-sticking and demands a more significant welding current or pulse energy. (Brand et al., 2015) also suggests in the research that both electrical resistance and quality of weld are influenced by weld energy. More weld energy would result in burning the material and electrode sticking effect. So optimal weld energy is necessary to achieve a good quality weld. In this research, optimal weld energy was chosen. CDDPA resistance spot welding machine has dual pulse weld energy, so in this research, two pulses of weld energy are used for welding the material. According to past research, two-pulse weld energy enhances the quality of the weld. Pulse 1 energy should be 30% or less than pulse two energy because pulse one energy is responsible for melting the material, and pulse two energy is responsible for the weld.

The figure 17 and 18 shows how the electrode sticks at low pressure to the workpiece, and a high amount of energy burns the material. The reason for the burning material is low electrode force. The heat generation is high when electrode force is low due to high contact resistance.

Figure 17. Electrode sticking on Nickel plated steel.

Figure 18. Electrode sticking on NI-plated copper.

While conducting experiments on Nickel-to-Nickel plated steel (Hilumin) and Nickel to Nickel plated copper, electrode pressure was set at 12 lbs/electrode, and the maximum stored energy is 320 ws.

3.3.2 Experiments on different dissimilar material combinations for checking weldability

This research tested the weldability of several similar materials and dissimilar material combinations using micro resistance spot welding. Initial experiments were conducted after adjusting the appropriate pressure to determine the weldability of different dissimilar materials. Below table 5 describes material combinations were welded to test their weldability.

Table 5. material combinations used for weldability checking experiments

Sr. No	Material combinations used for checking weldability
1	Nickel to Nickle plated steel (Hilumin)
2	Nickle to Nickle plated copper
3	Nickel plated copper to Nickel plated steel
4	Nickel to Copper
5	Copper to Nickel plated steel
6	Aluminum to copper
7	Aluminum to Nickel plated copper

For checking the weldability of various dissimilar material combinations, Various Process parameters like Pre weld delay, weld current, squeeze Time, Hold Time, and the delay between pulse, voltage, and Energy were chosen based on the Initial experiments. Every machine has different adjusting parameters. During the experiments, the CDDPA sunstone welding machine is used. Voltage, current, and energy are applied in two pulses. Each pulse has its upper and lower limit. Weldability checking experiments were conducted with two nuggets in which all parameters varied from higher to lower limits. The following table 6 shows variations in parameters in general.

Table 6. Process parameters variation

Sr. no	Parameters	Variations
1	Current	200 A to 10000 A
2	Voltage	0V to 20V
3	Squeeze time	150ms to 200ms
4	Pre-delay time	10ws to 50ws
5	Energy	100ws to 360ws
6	Hold time	10ms to 150ms

As (Alexy et al., 2019) found, welding conductive materials are complex as in this research. Conducive dissimilar material combinations were found difficult to weld while conducting weldability experiments on various dissimilar material combinations. Due to aluminum's strong heat conductivity and low electrical resistance, it was challenging to weld dissimilar conductive materials, such as aluminium to copper and aluminium to nickel-plated steel. Due to the low resistance of Aluminium, a very high current is needed to melt and establish the bond, which the CDDP A resistance welding machine cannot do because of its limited capacity to supply current. The experiments were performed using copper electrodes of modest diameter. However, thicker copper electrodes with a greater current capacity were needed to weld conductive metals like aluminium. This increased current eventually melted conductive metal like aluminium and produced a weld.

Similar results were found when experiments were conducted on dissimilar conductive materials such as copper-to-nickel-plated copper and copper-to-nickel. Copper also exhibits low resistance and solid thermal conductivity. Only a tiny amount of heat is produced when a high current is supplied to melt the material; copper has a high thermal conductivity, and this heat is transmitted quickly. Consequently, utilizing a CDDPA Resistance spot welding machine, copper was likewise found to be exceedingly tricky to weld.

More energy and current are needed when creating a weld with conductive materials. However, nickel's thermal conductivity is inferior to copper and aluminium, so less energy and current are needed to melt the material. Nickel also has a low melting temperature, making it simple to melt the metal and form a weld. When testing the weldability of various material combinations, the weld was produced when welding nickel-plated steel to nickel and nickel-plated steel to nickel-plated copper.

Below table 7 shows the different material combinations with their weldability.

Table 7. Results of weldability experiments

Material	Copper	Ni-plated steel	Nickel	Ni-plated copper	Aluminium
Ni-Plated steel	-	_	Weld obtained	-	-
Nickle	-	Weld obtained	Weld obtained	Weak weld obtained	-
Ni-plated copper	-	-	Weak weld obtained	-	-

Table 7 continues. Results of weldability experiments

Aluminium	-	-	-	-	-
Copper	-	-	-	-	-

After conducting initial experiments on the different dissimilar material combinations, weldable material combination was identified. Below table 8 shows the weldable combinations of dissimilar materials.

Table 8. identified weldable material combinations

Sr.no	Material combination
1)	Nickel to Nickel plated steel
2)	Nickel to Nickel plated copper

The above table shows that Nickel to Ni-plated steel / Ni-plated copper could be welded using CDDPA resistance spot welding. After identifying the weldable material combination, a series of experiments were conducted on both material combinations.

3.3.3 Experiments conducted on Nickel-to-Nickel plated steel

As can be seen in Fig.18 experimental setup was prepared. Resistance spot welding uses current to generate weld. In Their study of welding Nickle to Hilumin (Kumar, Masters, and Das, 2021) used the ANOVA (analysis of variations) technique to select the process parameters. They found that Weld current and Weld time significantly affect the weld joint quality. During the experiment, mostly weld current was varied because there is no adjustable weld time function in the Sunstone CDDPA welding machine; it automatically sets the desired weld time according to Heat Input. (Kumar et al., 2022) results also suggest that four nugget welds will reduce the connection resistance. So, in this experiment, welding was done with four nuggets.

During the welding experiments, parameters like squeeze time, hold time, pre-weld delay, and delay between pulses were constant, and their values can be seen in the below table 9.

Table 9. constant parameter's value

Sr. No	Parameters	Value
1	squeeze time	150ms
2	hold time	6ms
3	pre weld delay	30ms
4	delay between pulses	20ms

On the other hand, current, voltage, and energy were varied during the experiments. The below table 10 shows conducted experiments with the changing parameters. Approximately 42 experiments were systematically performed on the Nickel-to-Nickel plated steel, mainly changing the welding current.

Table 10. conducted experiments on Nickel-to-nickel plated steel (Hilumin)

Sr.no	Material		Current			Voltage		Energy		Result
			Pulse 1	Pulse 2		Pulse 1	Pulse 2	Pulse 1	Pulse 2	
1	Nickel to Ni-plated steel	Upper Limit	500A	1500A	Upper Limit	10V	10V	90ws	90ws	weld obtained

Table 10 continues. conducted experiments on Nickel-to-nickel plated steel (Hilumin)

		lower Limit	500 A	150 0A	lower Limit	10 V	10 V			
2	Nickel to Ni-plated steel	Upper Limit	800 A	800 A	Upper Limit	18 V	0 V	90 ws	90 ws	weld obtained
		lower Limit	500 A	500 A	lower Limit	16 V	0 V			
3	Nickel to Ni-plated steel	Upper Limit	800 A	800 A	Upper Limit	18 V	0 V	90 ws	90 ws	weld obtained
		lower Limit	200 0A	200 0A	lower Limit	16 V	0 V			
4	Nickel to Ni-plated steel	Upper Limit	100 0A	800 A	Upper Limit	18 V	0 V	90 ws	90 ws	weld obtained
		lower Limit	200 0A	220 0A	lower Limit	16 V	0 V			

Table 10 continues. conducted experiments on Nickel-to-nickel plated steel (Hilumin)

5	Nickel to Ni-plated steel	Upper Limit	200 A	380 0A	Upper Limit	10 V	10 V	10 ws	150 ws	weld obtained
		lower Limit	200 A	380 0A	lower Limit	10 V	10 V			
6	Nickel to Ni-plated steel	Upper Limit	300 A	380 0A	Upper Limit	10 V	10 V	10 ws	150 ws	weld obtained
		lower Limit	300 A	380 0A	lower Limit	10 V	10 V			
7	Nickel to Ni-plated steel	Upper Limit	800 A	800 A	Upper Limit	10 V	10 V	10 ws	150 ws	Low strength weld
		lower Limit	500 A	500 A	lower Limit	10 V	10 v			
8	Nickel to Ni-plated steel	Upper Limit	800 A	100 0A	Upper Limit	10 V	10 V	10 ws	150 ws	Low strength weld
		lower Limit	800 A	100 0A	lower Limit	10 V	10 v			
9	Nickel to Ni-plated steel	Upper Limit	100 0A	800 A	Upper Limit	10 V	10 V	10 ws	150 ws	Low strength weld

Table 10 continues. conducted experiments on Nickel-to-nickel plated steel (Hilumin)

		lower Limit	200 0A	220 0A	lower Limit	10 V	10 V			
1 0	Nickel to Ni-plated steel	Upper Limit	800 A	200 0A	Upper Limit	10 V	10 V	3w s	157 ws	weld not obtained
		lower Limit	800 A	200 0A	lower Limit	10 V	10 V			
1 1	Nickel to Ni-plated steel	Upper Limit	800 A	200 0A	Upper Limit	10 V	10 V	0w s	50 ws	weld not obtained
		lower Limit	800 A	200 0A	lower Limit	10 V	10 V			
1 2	Nickel to Ni-plated steel	Upper Limit	100 A	200 0A	Upper Limit	10 V	10 V	30 ws	150 ws	weld obtained
		lower Limit	100 A	200 0A	lower Limit	10 V	10 V			
1 3	Nickel to Ni-plated steel	Upper Limit	100 0A	220 0A	Upper Limit	10 V	10 V	30 ws	150 ws	weld obtained
		lower Limit	100 0A	220 0A	lower Limit	10 V	10 V			
1 4	Nickel to Ni-plated steel	Upper Limit	150 0A	250 0A	Upper Limit	10 V	10 V	30 ws	150 ws	weld obtained

Table 10 continues. conducted experiments on Nickel-to-nickel plated steel (Hilumin)

		lower Limit	150 0A	250 0A	lower Limit	10 V	10 V			
1 5	Nickel to Ni-plated steel	Upper Limit	100 0A	250 0A	Upper Limit	10 V	10 V	30 ws	150 ws	black spot-on weld
		lower Limit	800 A	220 0A	lower Limit	10 V	10 V			
1 6	Nickel to Ni-plated steel	Upper Limit	800 A	250 0A	Upper Limit	10 V	10 V	30 ws	150 ws	black spot-on weld
		lower Limit	700 A	220 0A	lower Limit	10 V	10 V			
1 7	Nickel to Ni-plated steel	Upper Limit	500 A	250 0A	Upper Limit	10 V	10 V	30 ws	150 ws	weld obtained
		lower Limit	200 A	220 0A	lower Limit	10 V	10 V			
1 8	Nickel to Ni-plated steel	Upper Limit	200 A	250 0A	Upper Limit	10 V	10 V	30 ws	150 ws	weld obtained
		lower Limit	100 A	250 0A	lower Limit	10 V	10 V			

Table 10 continues. conducted experiments on Nickel-to-nickel plated steel (Hilumin)

19	Nickel to Ni-plated steel	Upper Limit	200 A	2000A	Upper Limit	10 V	10 V	30 ws	150 ws	weld obtained
		lower Limit	100 A	1800A	lower Limit	10 V	10 V			
20	Nickel to Ni-plated steel	Upper Limit	200 A	1800A	Upper Limit	10 V	10 V	30 ws	150 ws	weld obtained
		lower Limit	100 A	1500A	lower Limit	10 V	10 V			
21	Nickel to Ni-plated steel	Upper Limit	200 A	1700A	Upper Limit	10 V	10 V	30 ws	150 ws	black spot-on weld
		lower Limit	100 A	1300A	lower Limit	10 V	10 V			
22	Nickel to Ni-plated steel	Upper Limit	200 A	1500A	Upper Limit	10 V	10 V	30 ws	150 ws	weld obtained
		lower Limit	100 A	1500A	lower Limit	10 V	10 V			
23	Nickel to Ni-plated steel	Upper Limit	1000A	2200A	Upper Limit	10 V	10 V	30 ws	150 ws	weld obtained
		lower Limit	1000A	2200A	lower Limit	10 V	10 V			

Table 10 continues. conducted experiments on Nickel-to-nickel plated steel (Hilumin)

24	Nickel to Ni-plated steel	Upper Limit	1000A	2400A	Upper Limit	10 V	10 V	30 ws	150 ws	Welds obtain
		lower Limit	1000A	2400A	lower Limit	10 V	10 V			
25	Nickel to Ni-plated steel	Upper Limit	1000A	2600A	Upper Limit	10 V	10 V	30 ws	150 ws	Welds obtain
		lower Limit	1000A	2600A	lower Limit	10 V	10 V			
26	Nickel to Ni-plated steel	Upper Limit	1000A	2800A	Upper Limit	10 V	10 V	30 ws	150 ws	weld obtained
		lower Limit	1000A	2800A	lower Limit	10 V	10 V			
27	Nickel to Ni-plated steel	Upper Limit	1000A	3000A	Upper Limit	10 V	10 V	30 ws	150 ws	weld obtained
		lower Limit	1000A	3000A	lower Limit	10 V	10 V			
28	Nickel to Ni-plated steel	Upper Limit	1000A	3200A	Upper Limit	10 V	10 V	30 ws	150 ws	weld obtained
		lower Limit	1000A	3200A	lower Limit	10 V	10 V			

Table 10 continues. conducted experiments on Nickel-to-nickel plated steel (Hilumin)

29	Nickel to Ni-plated steel	Upper Limit	1000A	3400A	Upper Limit	10 V	10 V	30 ws	150 ws	weld obtained
		lower Limit	1000A	3400A	lower Limit	10 V	10 V			
30	Nickel to Ni-plated steel	Upper Limit	1000A	3800A	Upper Limit	10 V	10 V	30 ws	150 ws	weld obtained
		lower Limit	1000A	3800A	lower Limit	10 V	10 V			
31	Nickel to Ni-plated steel	Upper Limit	200 A	3800A	Upper Limit	10 V	10 V	30 ws	150 ws	weld obtained
		lower Limit	200 A	3800A	lower Limit	10 V	10 V			
32	Nickel to Ni-plated steel	Upper Limit	100 A	3800A	Upper Limit	10 V	10 V	30 ws	150 ws	weld obtained
		lower Limit	100 A	3800A	lower Limit	10 V	10 V			
33	Nickel to Ni-plated steel	Upper Limit	150 A	3800A	Upper Limit	10 V	10 V	30 ws	150 ws	weld obtained
		lower Limit	150 A	3800A	lower Limit	10 V	10 V			

Table 10 continues. conducted experiments on Nickel-to-nickel plated steel (Hilumin)

3 4	Nickel to Ni-plated steel	Upper Limit	250 A	380 0A	Upper Limit	10 V	10 V	30 ws	150 ws	weld obtained
		lower Limit	250 A	380 0A	lower Limit	10 V	10 V			
3 5	Nickel to Ni-plated steel	Upper Limit	300 A	380 0A	Upper Limit	10 V	10 V	30 ws	150 ws	weld obtained
		lower Limit	300 A	380 0A	lower Limit	10 V	10 V			
3 6	Nickel to Ni-plated steel	Upper Limit	350 A	380 0A	Upper Limit	10 V	10 V	30 ws	150 ws	weld obtained
		lower Limit	250 A	380 0A	lower Limit	10 V	10 V			
3 7	Nickel to Ni-plated steel	Upper Limit	400 A	380 0A	Upper Limit	10 V	10 V	30 ws	150 ws	weld obtained
		lower Limit	400 A	380 0A	lower Limit	10 V	10 V			
3 8	Nickel to Ni-plated steel	Upper Limit	500 A	380 0A	Upper Limit	10 V	10 V	30 ws	150 ws	weld obtained
		lower Limit	500 A	380 0A	lower Limit	10 V	10 V			

Table 10 continues. Conducted experiments on Nickel-to-nickel plated steel (Hilumin)

39	Nickel to Ni-plated steel	Upper Limit	2170A	4000A	Upper Limit	10 V	10 V	30 ws	150 ws	weld obtained
		lower Limit	2000A	3800A	lower Limit	10 V	10 V			
40	Nickel to Ni-plated steel	Upper Limit	3000A	4000A	Upper Limit	10 V	10 V	30 ws	150 ws	weld obtained
		lower Limit	2000A	3800A	lower Limit	10 V	10 V			
41	Nickel to Ni-plated steel	Upper Limit	2800A	4000A	Upper Limit	10 V	10 V	30 ws	150 ws	weld obtained
		lower Limit	2000A	3800A	lower Limit	10 V	10 V			
42	Nickel to Ni-plated steel	Upper Limit	2700A	4000A	Upper Limit	10 V	10 V	30 ws	150 ws	weld obtained
		lower Limit	2000A	3800A	lower Limit	10 V	10 V			

When applied energy pulse one was set to zero, the weld was not obtained because pulse 1 is responsible for melting the material. If it is subjected to zero, no material will melt, and eventually, the weld is not formed. Above Every experiment was conducted two times to achieve precision and accuracy. The weld quality was decided upon using a qualitative analysis conducted by hand. Hand Pull Test ensures the quality of weld strength. In this test, welded material was subjected to stress from both sides to ensure excellent weld strength. After ensuring the reliability of the welded joint, nine weld samples based on the Heat input were taken.

As seen in the above table, mainly current was changed from lower limit to upper limit because Resistance spot welding is a thermal welding technique that uses heat as a critical component to weld two metal parts together. As per Joule's theory and according to equation 2 below, the quantity of heat produced while resistance spot welding depends mainly on weld current and welding time, and the resistance of the metals being welded.

$$Q = I^2RT \tag{2}$$

The primary factor considered when taking samples was the Heat input. Here in resistance spot welding, heat input is directly proportional to the welding current. Accordingly, to (Kumar et al., 2022), welding current directly affects the electro-mechanical properties of the welded joint. Hence, welding Samples were taken from low to high current values in this research. The figure 19 below shows the welded samples, and the table 11 shows the nine samples with the value of their parameter.

Figure 19. Nickel to Nickel plated steel welded samples.

Table 11. Nine sample’s parameters

Sr. No	Material		Current			Voltage		Energy		Result
			Pulse 1	Pulse 2		Pulse 1	Pulse 2	Pulse 1	Pulse 2	
1	Nickel to Ni-plated steel	Upper Limit	200 A	3800A	Upper Limit	10 V	10 V	30 ws	150 ws	weld obtained
		lower Limit	200 A	3800A	lower Limit	10 V	10 V			

Table 11 continues. Nine sample's parameters

2	Nickel to Ni-plated steel	Upper Limit	300 A	380 0A	Upper Limit	10 V	10 V	30 ws	150 ws	weld obtained
		lower Limit	300 A	380 0A	lower Limit	10 V	10 V			
3	Nickel to Ni-plated steel	Upper Limit	100 0A	320 0A	Upper Limit	10 V	10 V	30 ws	150 ws	weld obtained
		lower Limit	100 0A	320 0A	lower Limit	10 V	10 V			
4	Nickel to Ni-plated steel	Upper Limit	100 0A	280 0A	Upper Limit	10 V	10 V	30 ws	150 ws	weld obtained
		lower Limit	100 0A	280 0A	lower Limit	10 V	10 V			
5	Nickel to Ni-plated steel	Upper Limit	400 A	380 0A	Upper Limit	10 V	10 V	30 ws	150 ws	weld obtained
		lower Limit	400 A	380 0A	lower Limit	10 V	10 V			
6	Nickel to Ni-plated steel	Upper Limit	217 0A	400 0A	Upper Limit	10 V	10 V	30 ws	150 ws	weld obtained

Table 11 continues. Nine sample’s parameters

		lower Limit	200 0A	380 0A	lower Limit	10 V	10 V			
7	Nickel to Ni- plated steel	Upper Limit	300 0A	400 0A	Upper Limit	10 V	10 V	30 ws	150 ws	weld obtained
		lower Limit	200 0A	380 0A	lower Limit	10 V	10 V			
8	Nickel to Ni- plated steel	Upper Limit	280 0A	400 0A	Upper Limit	10 V	10 V	30 ws	150 ws	weld obtained
		lower Limit	200 0A	380 0A	lower Limit	10 V	10 V			
9	Nickel to Ni- plated steel	Upper Limit	270 0A	400 0A	Upper Limit	10 V	10 V	30 ws	150 ws	weld obtained
		lower Limit	200 0A	380 0A	lowe	10 V	10 V			

3.3.4 Visual inspection of the welded samples

A post-weld visual analysis is often performed to verify the finished weld's quality. Undersized weld undercuts, overlapping, superficial cracks, surface porosity, underfill, insufficient root penetration, burning out, and inadequate reinforcing are typical welding abnormalities identified via physical observation. In this research, visual inspection was performed individually for every sample after taking samples. A few samples had minor cracks and burning weld nuggets, but they were insignificant. Here below figure 20 and 21 represent sample number 9 and sample no 4.

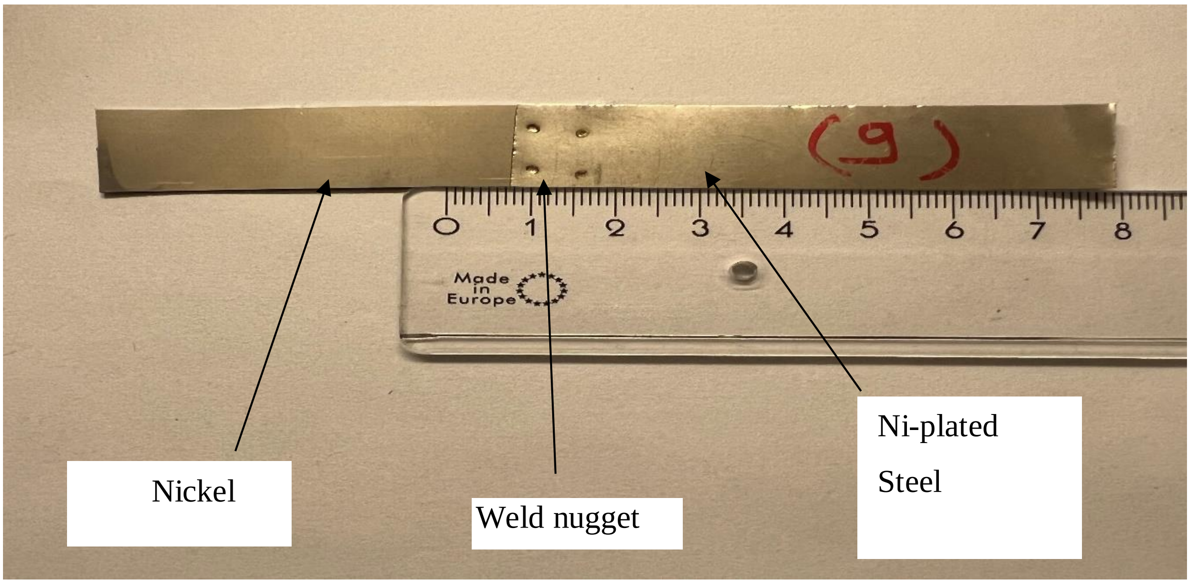

Figure 20. Nickel to Ni-plated steel welded sample number 9.

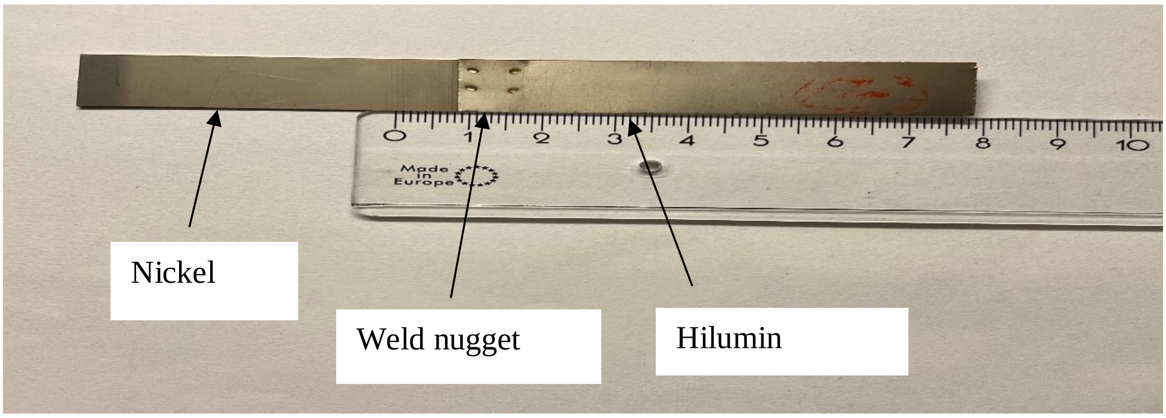

Figure 21. nickel to Ni-plated steel welded sample number 6.

3.3.5 Experiments on Nickel-to-Nickel plated copper

As can be seen in table no 8, weldable materials were identified. Some experiments were performed to join the nickel-plated copper to nickel. During these experiments, only the welding current was changed; all remaining parameters were constant. Here in the below table 12, experiments with parameters can be seen.

Table 12. welded samples with parameters

Sr. No	Material		Current			Voltage		Energy		Result
			Pulse 1	Pulse 2		Pulse 1	Pulse 2	Pulse 1	Pulse 2	
1	Nickel to Ni-plated copper	Upper Limit	1000 A	3700 A	Upper Limit	10 V	10 V	10 ws	150ws	Weak weld obtained
		lower Limit	2000 A	3500 A	lower Limit	10 V	10 V			
2	Nickel to Ni-plated copper	Upper Limit	1200 A	4000 A	Upper Limit	10 V	10 V	10 ws	150ws	Weak weld obtained

Table 12 continues. welded samples with parameters

3	Nickel to Ni-plated copper	Upper Limit	2000A	5000A	Upper Limit	10V	10V	10ws	150ws	Weak weld obtained
		lower Limit	2200A	2000A	lower Limit	10V	10V			
4	Nickel to Ni-plated copper	Upper Limit	3000A	5000A	Upper Limit	10V	10V	10ws	150ws	Weak weld obtained
		lower Limit	1200A	2200A	lower Limit	10V	10V			
5	Nickel to Ni-plated copper	Upper Limit	4000A	4500A	Upper Limit	10V	10V	10ws	150ws	Weak weld obtained
		lower Limit	3000A	4000A	lower Limit	10V	10V			
6	Nickel to Ni-plated copper	Upper Limit	5000A	4000A	Upper Limit	10V	10V	10ws	150ws	weak weld obtained

Table 12 continues. welded samples with parameters

			lower Limit	5500A	4100A	lower Limit	10V	10V				
7	Nickel to Ni-plated copper		Upper Limit	5000A	6000A	Upper Limit	10V	10V	10ws	150ws	Weak weld obtained	
			lower Limit	5500A	6500A	lower Limit	10V	10v				
8	Nickel to Ni-plated copper		Upper Limit	1000A	3300A	Upper Limit	10V	10V	10ws	150ws	weak weld obtained	
			lower Limit	500A	2000A	lower Limit	10V	10v				
9	Nickel to Ni-plated copper		Upper Limit	1200A	3500A	Upper Limit	10V	10V	10ws	150ws	weak weld obtained	
			lower Limit	1000A	2500A	lower Limit	10V	10V				

Table 12 continues. welded samples with parameters

10	Nickel to Ni-plated copper	Upper Limit	1500A	3500A	Upper Limit	10V	10V	10 ws	150ws	weak weld obtained
		lower Limit	1100A	2500A	lower Limit	10V	10V			

Due to copper's high heat conductivity and low electrical resistance, a large current was used to join the nickel-to-nickel-plated copper metals, as shown in the table above. During the experiments, nickel was positioned on top of nickel-plated copper, and a large current was delivered to the workpiece to produce a weld. However, this weld was exceedingly weak. It was found that the nickel material only formed bonds with the microlayer of nickel above the copper, not with the copper material downside. The copper requires a higher amount of welding current to melt and join the copper with nickel, which the CDDPA welding machine cannot deliver due to it limited capabilities. The below figure 22 shows the welded joint between nickel and nickel-plated copper.

Figure 22. Nickel to Nickel plated copper welded joint.

The figure above shows that nickel- and nickel-plated copper were joined. The weld quality was tested by pull test, done manually using hands. When the weld was subjected to stress from both sides, the welded joint broke out due to the low weld strength. That is why different processes like resistance measurement and microanalysis were not performed on this material combination in this research.

3.3.6 Microanalysis of welded samples

The microscopical analysis is performed to look at the cross-section of a welded junction and disclose microscopic qualities. Microscopic analysis investigates hot and cold fractures, holes, melt deficiencies, and other properties.

Four samples among the nine welded samples of nickel-to-nickel-plated steel were taken for the microanalysis of the welded joint. Samples were taken considering the heat input applied to them from lower welding current to higher welding current. Here below table 13 shows the samples used for the microscopic analysis.

Table 13. welded samples taken for the micro analysis

SR. NO	Material		Current			Voltage		Energy		Result
			Pulse 1	Pulse 2		Pulse 1	Pulse 2	Pulse 1	Pulse 2	
1	Nickel to Ni-plated steel	Upper Limit	300A	3800A	Upper Limit	10V	10V	30 ws	150 ws	weld obtained
		lower Limit	300A	3800A	lower Limit	10V	10V			
2	Nickel to Ni-plated steel	Upper Limit	1000A	2800A	Upper Limit	10V	10V	30 ws	150 ws	weld obtained
		lower Limit	1000A	2800A	lower Limit	10V	10V			
3	Nickel to Ni-plated steel	Upper Limit	2170A	4000A	Upper Limit	10V	10V	30 ws	150 ws	weld obtained
		lower Limit	2000A	3800A	lower Limit	10V	10V			

Table 13 continues. welded samples taken for the micro analysis

4	Nickel To Ni-Plated Steel	Upper Limit	2700a	4000a	Upper Limit	10 v	10 v	30 ws	150 ws	Weld Obtained
		lower Limit	2000A	3800A	lower Limit	10 V	10 V			

For microstructural evaluation, welded samples cross sectioned from the middle, a cutter Discotom was used to cut the specimen. Cut specimens were then mounted in ClaroCit Powder/ClaroCit Liquid mixture and mechanically ground using #500 and #800 SiC paper. Polishing was made using a three µm diamond suspension. Specimen were etched using Kroll's Reagent (15 ml HF, 5 ml HNO3, and 85 % H20) for 45 s to reveal the micro- and macrostructure. The macroscopic examination was made using Wild Harburg macroscope and XCAM 1080p software. Microstructure examination was analysed under an optical microscope Meiji IM 7530 and Image View-software.

3.3.7 Resistance measurement method

The resistance of the welded joint was assessed using a four-point evaluation procedure which is used by (Brand et al., 2015) and (Kumar, Masters, and Das, 2021) in their Research. This research employs the same methodology to determine the welded joint's resistance. The schematic diagram of resistance measurement of welded samples is shown in figure 23.

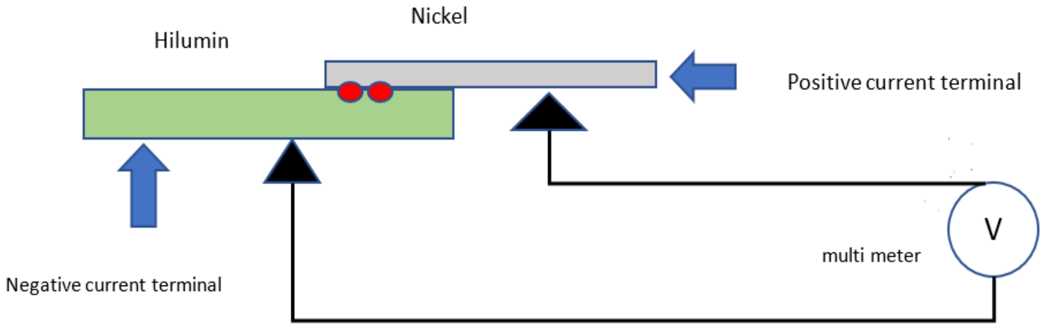

Figure 23. schematic diagram of resistance measurement procedure.

In the following figure 24, nickel and Hilumin are put through the current application, and their potential differences are measured with a multimeter. Resistance across welded joints can be measured using Ohm's law. When current is transmitted through the workpiece in this resistance spot welding, heat is produced owing to resistive heat loss. The temperature around the welded connection ultimately rises due to this heat loss, and a thermal camera is employed to measure it. The below Equation 3, explicates Ohm's Law.

$$V = IR \tag{3}$$

Here V= potential difference between the two terminals

R = resistance of the strip

I = current passing through the welded strip

Nine weld samples applied to different currents, and due to the applied current temperature rise phenomena and the potential difference between the terminal were reported. Here, while measuring the welded joint resistance, two methods are used.

In the first method, ohm’s law is used. Ohm's law postulates that the current passing through a conductor connecting two points is directly proportionate to the voltage existing across those two points.

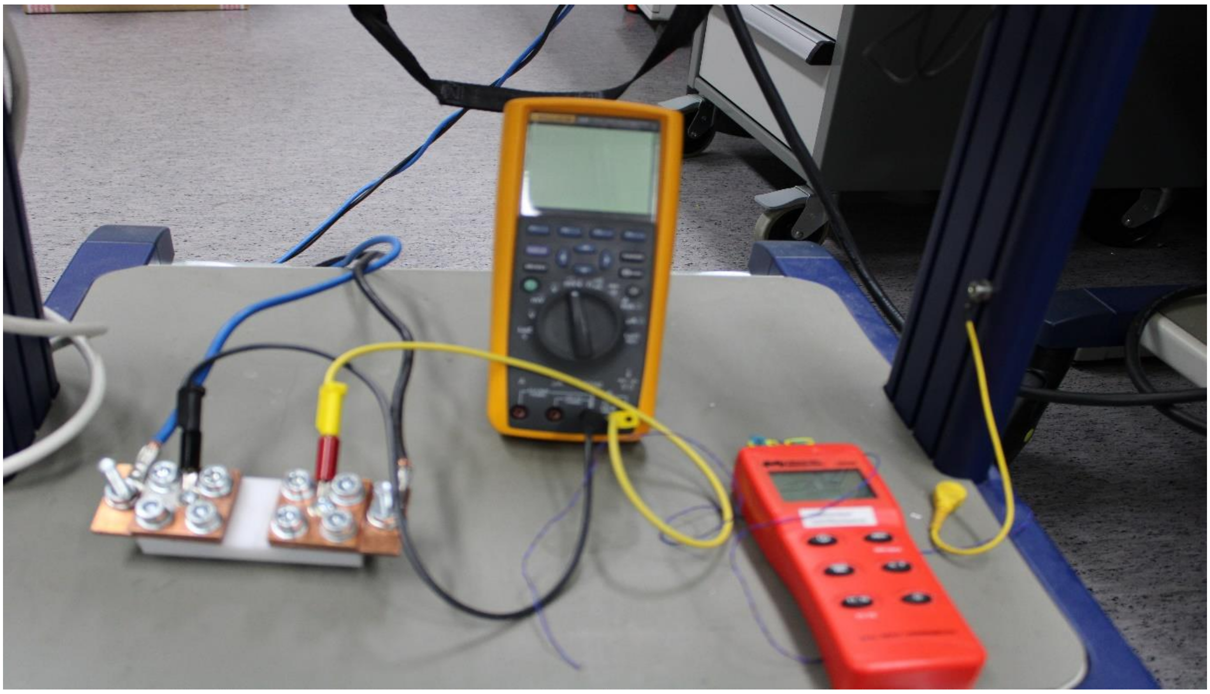

Figure 24. resistance measurement actual setup.

The above eq.3 was used to find the resistance value based on the voltage drop across the strip. the second method is to find the resistance value based on the resistivity of the strip. As seen in the below figure, here, two dissimilar metals are joined together, and both have a different resistivity, and both are joined in parallel with spot welding. In this case, resistance can be found based on the resistivity of the particular material and measurement dimension.

As can be seen in the below figure, a resistance setup was made, and the electrical resistance measurement was conducted on the nine welded samples.

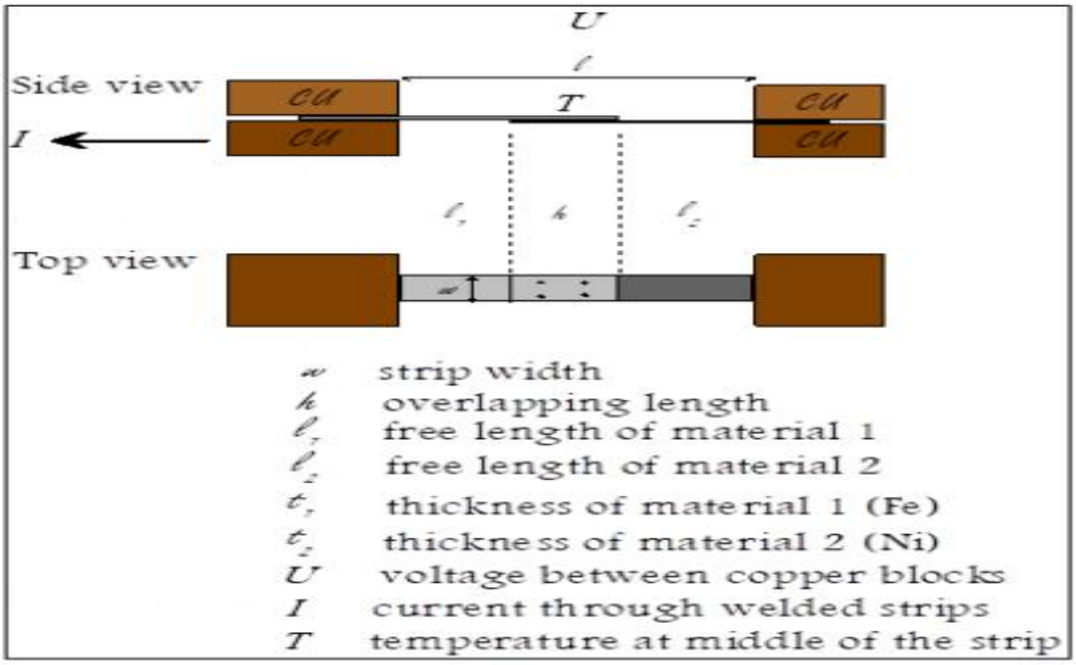

Figure 25. resistance measurement setup with length.

The data of the welded sample 2 is given below in table 14 to understand how resistance could be measured differently.

Table 14. welded strip two measurement data

Welded strip – 2				
I(A)	U(mV)	T(°C)		
15.9	16.33	23		
35.7	37.5	30		
42.4	45.3	35.6		
51.9	57.5	45.5		
72.3	90.8	79.9		
L(mm)	w(mm)	l_1 (mm)	h(mm)	l_2 (mm)
21.45	9.85	6.45	9.75	5.25

Equation 4 articulates the application of Ohm's Law to the measurement data presented above.

$$I = V / R \tag{4}$$

Then the resistance value of the welded sample 2 is shown in the table 15.

Table 15. resistance measurement by using ohm's law

Welded strip	2			
I (A)	U (mV)	T (°C)	R (U/I) mΩ	
			1.03	
15.9	16.33	23		
35.7	37.5	30	1.05	
42.4	45.3	35.6	1.07	
51.9	57.5	45.5	1.11	
72.3	90.8	79.9	1.26	
l (mm)	w (mm)	l1 (mm)	h (mm)	l2(mm)
21.45	9.85	6.45	9.75	5.25

However, as shown in figure 26, both the strips are connected in parallel by resistance spot welding, and both the materials are different, so while determining welded joint resistance, their resistivity should be considered.

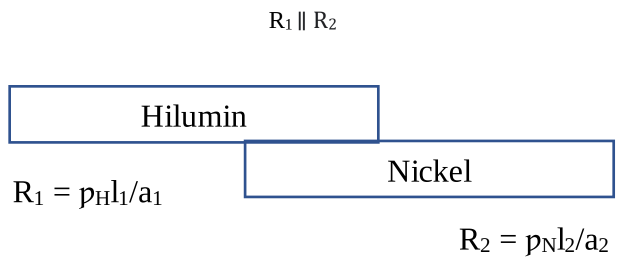

Figure 26. Lap configuration of Hilumin and Nickel.

Here as per the given lap joint configuration above equation 5 can be written as

$$R_H = \rho_H l_1 / a_1 \tag{5}$$

Here, $a_1 = w_1 * t_1$ and ρ_H = Voltage/Current * Area/length

Where, ρ_H = Resistivity of Hilumin

l1 = given length as per dimension

a1 = area of the strip

Similarly, the Nickel strip R_N resistance can be found using the equation below 6.

$$R_N = \rho_N l_2/a_2 \tag{6}$$

After measuring both the strip resistance, parallel welded joint resistance can be found using the below equation 7.

$$R_H \parallel R_N \qquad (7)$$

$$= \rho_H l_0/a_0 \parallel \rho_N l_0/a_0 \qquad (8)$$

Here l_0 = overlap length

a_0 = overlap area

The following table 16 shows the resistance of the welded strip two after using the above equations.

Table 16. resistance measurement considering resistivity of the materials

I (A)	U(mv)	T°c	R_H	$R_H \parallel R_N$	R_N
15.9	16.33	23	0.20	0.22	0.45
35.7	37.5	30	0.20	0.23	0.46
42.4	45.3	35.6	0.21	0.23	0.47
51.9	57.5	45.5	0.21	0.24	0.49
72.3	90.8	79.9	0.24	0.26	0.54

4 Testing and Characterization

Figure 27 depicts a cross-section of the welded joints under various welding conditions. As visible, the welded junction was made of melted nickel- and nickel-plated steel. The melted nickel is readily visible all over the nickel-plated steel in the figure.

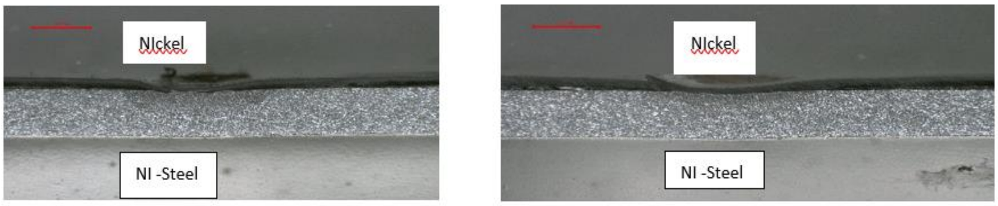

Figure 27 . cross section of welded sample 2.1 (left), and welded sample 4.1 (right).

Cross section of welded samples 2 and welded samples 4 was analyzed at the micro level 100 µm. It can be clearly seen that increasing the temperature creates a void in the microstructure. And this void contributes to weakening the quality of the weld.

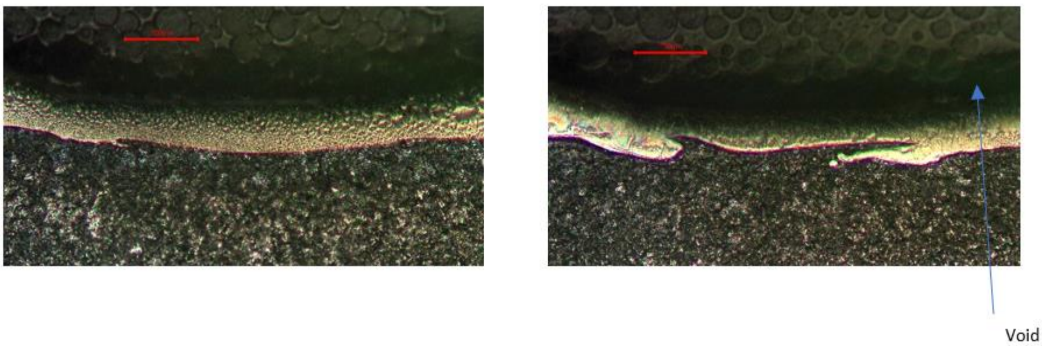

Figure 28. cross section of welded joint 2 (left) and welded joint 4(right) at 100 µm

5 Result

As can be observed from the methodology section, welding tests were done in this study using a lap joint configuration between 0.5 mm nickel-plated steel (Hilumin) and 0.1 nickel strip. Weldable material was discovered after determining the weldability of the various dissimilar material combinations, as shown in table 8. The two material pairings, nickel-plated steel to Nickel and Nickel to nickel-plated copper, were then the subject of systematic studies. After examining the weld characteristics of the two material combinations, welded samples of nickel-plated steel to Nickel were generated and selected for the microanalysis and measurements of the welded joint resistance.

5.1 Analysis of electrical contact resistance

The nine samples, which can be seen in table 11, were chosen for the electrical resistance measurements and temperature investigation. Every resistance measurement test is performed two times, and the measurement of the potential difference and currents is reported along with the temperature, as discussed earlier in the methodology section.

In the resistance measurement, the below figure 29 shows the behaviour of the welded strip in terms of resistance. Resistance is increased while the applied current is increased. When current is applied to the welded samples, heat is generated due to the resistive heat loss, and this resistive heat loss plays a crucial role in increasing the resistance in the welded strip. It works like a loop.

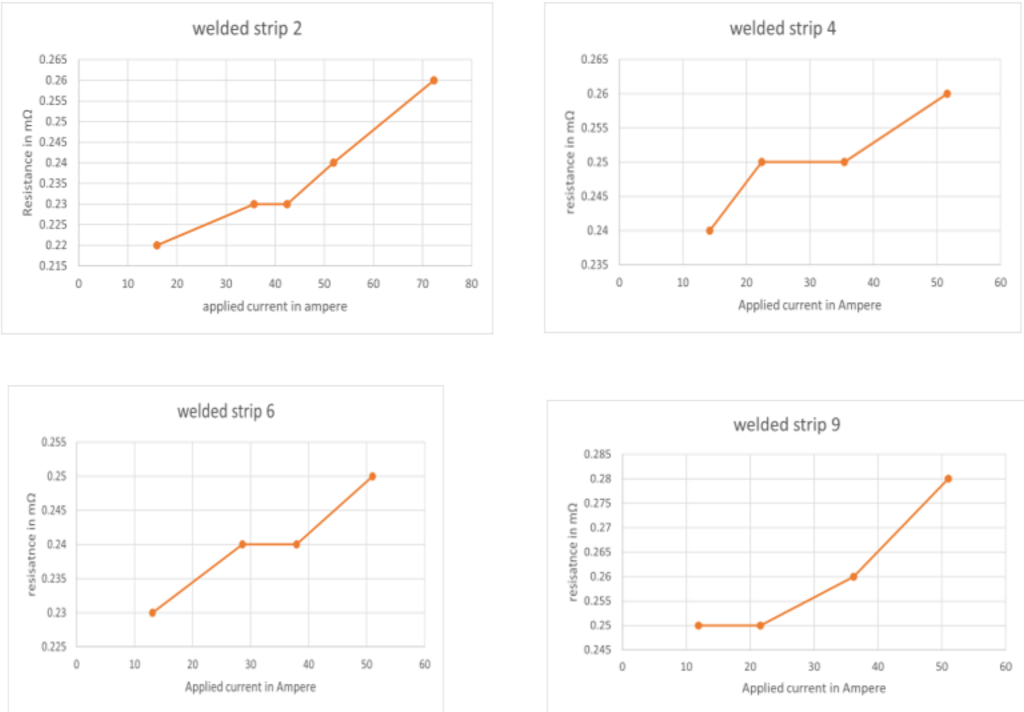

Figure 29. resistance vs current graph for the welded samples.

The below table 17 to table 20 show the resistance value concerning the current in different welded samples. During the resistance measurement for every welded sample, the current was varied. The above table shows that with current, resistance also varies, but the difference between varied resistance to current is negligible. For example, different currents (13.1 A, 28.6A, 37.9A, and 51A) was applied to welded sample 6, and the measured resistance for the welded strip 6 is (0.23 mΩ,0.24 mΩ,0.24 mΩ, and 0.25 mΩ) which shows small increment in resistance.

Table 17. welded strip 4 resistance with respect to current

I (A)	R (mΩ)
11.9	0.25
21.6	0.25
36.2	0.26
51	0.28

Table 18. welded strip 2 resistance with respect to current

I (A)	R(mΩ)
15.9	0.22
35.7	0.23
42.4	0.23
51.9	0.24
72.3	0.26

Table 19. welded strip 6 resistance with respect to current

I (A)	R(mΩ)
13.1	0.23
28.6	0.24
37.9	0.24
51	0.25

Table 20. welded strip 9 resistance with respect to current

I (A)	R(mΩ)
14.2	0.24
22.4	0.25
35.4	0.25
51.6	0.26

While measuring the connection resistance of the 0.5mm Hilumin and 0.1mm nickel strip, the lowest resistance is recorded in welded sample two. The contact resistance value is 0.22mΩ, while the applied current was 15.9A. Moreover, the maximum resistance was recorded in welded sample seven, and the resistance value was 0.31 mΩ while the applied current was 58A. As observed from the instances mentioned above, the resistance values of the welded strip increase with current, but the increment is relatively slight in milliohm. Therefore, the performance of the battery pack is not significantly impacted.

5.2 Analysis of joint temperature rise

Standard battery packs contain a thermal management system. This system primarily concentrates on the external cooling of the cells. One of the significant stresses that may have an impact on battery efficiency is the rising joint heat. High temperatures can increase aging and encourage the formation of solid electrolyte contact in battery cells, which can result in an early breakdown.

Here in this research while measuring the temperature across the welded samples, when current passes through the welded samples, due to the resistive heat loss, the temperature rises surrounding the welded strip and joint. So, it is essential to study the resistance variation concerning the temperature rise. In the below figure it is clearly seen that when current passes through the welded samples are increased, temperature is also increased.

For instance, in welded sample 2, the temperature is recorded as 23 °C at 15.9A, 30 °C at 35.7A, 35.6°C at 42.4A, and so on. Simultaneously in welded sample 9, the temperature is recorded at 25.6°C at 11.9A, 27.8°C at 21.6A, 36.1°C at 36.2A and 52.7°C at 51A.

Here below in figure 30, in welded samples 2,4,6 and 9, when current is applied 51A, then the temperature was recorded at 45.5°C, 49.4°C,49.2°C, and 52.7°C respectively. Previous research shows that Lithium-ion batteries can work smoothly at 45°C. When the temperature exceeds higher than that, then it will create a negative impact on the battery pack efficiency. Below results highlight the value of selecting the projected pass current value to lessen the detrimental effects of elevated joint temperatures on battery packs.

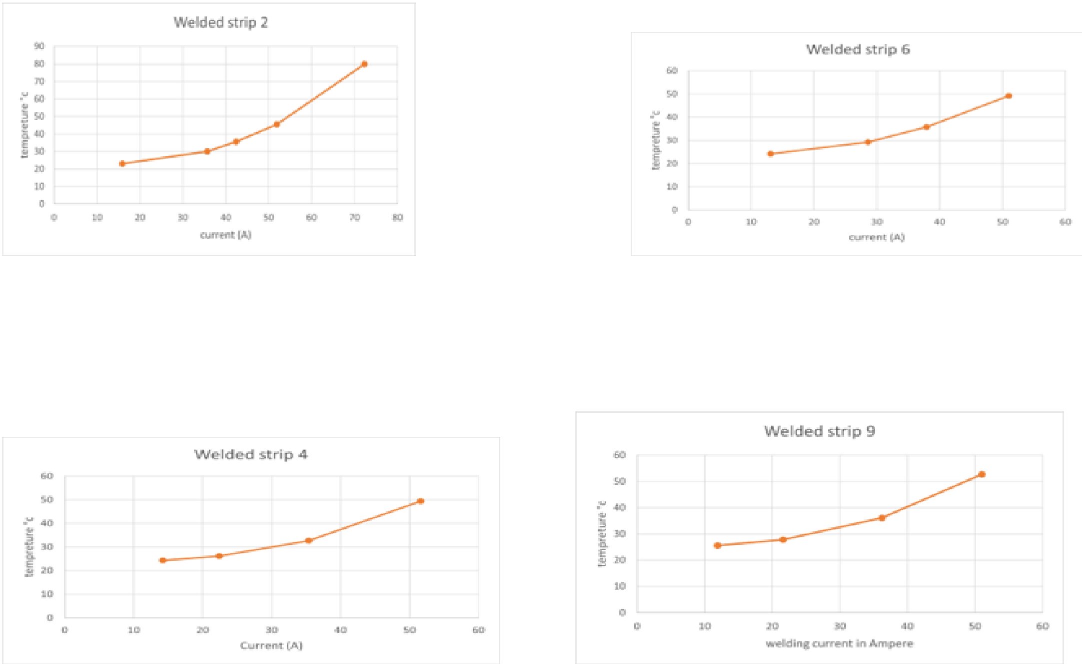

Figure 30. Temperature measurement of the welded samples.

6 Discussion

In this thesis, we have explored the electrical performance of welded joints between battery cell tabs and busbars for battery pack applications, with a specific focus on dissimilar material combinations. The results suggest that an increase in current passing through the welded joint leads to an increase in resistance, although the magnitude of this increment remains in the milliohm range, thereby minimally affecting the overall performance of electric vehicle battery packs. However, our results indicate a significant rise in temperature within the welded joint as current passes through it due to resistive heat loss, potentially impacting battery pack efficiency. Our research identified nickel and nickel-plated steel as suitable material combinations for resistance spot welding, as these materials are commonly used in the automotive industry for battery pack applications. While past research (Kumar et al., 2022) investigated contact resistance using thinner materials, our findings align closely, with slight variations due to material thickness differences. Additionally, we addressed the challenge of electrode sticking by employing higher electrode force and optimizing energy input, addressing an issue noted by (Ely and Zhou, 2001). However, it's worth noting that this study has limitations. Notably, it did not fully investigate conductive dissimilar materials such as copper and aluminium, which are increasingly prevalent in modern battery pack applications. Future research opportunities lie in exploring resistance spot welding for connecting these conductive materials.

6.1 Comparison and connection with former research

While various welding techniques are available for joining cell tabs, the selection must meet the requirements for combining dissimilar materials cost-effectively. Resistance Spot Welding (RSW) emerged as an attractive choice due to its low initial capital requirements, fast processing times, low electrical contact resistance, and corrosion resistance. Nickel, identified in previous studies (Brand et al., 2015) (Alexy et al., 2019), was confirmed as a suitable material for battery tab welding due to its lower conductivity. Moreover, studies by (Phichai et al., 2019) suggested the potential to improve electrical performance by adjusting welding parameters and employing thicker materials (Lee et al., 2016). However, despite the advancements, comprehensive investigations into electrical contact resistance within micro-RSW joints, particularly those involving 0.5 mm Ni-plated steel connecting tabs to Nickel battery cell terminals within a battery pack, remain scarce. This research strives to bridge this gap by thoroughly evaluating electrical contact resistance, a key factor that, when optimized, can enhance overall electrical performance, and contribute to achieving sustainable zero-carbon emission goals.

This research journey was guided by the pressing need to address the formidable challenges of welding dissimilar materials for battery pack applications, informed by the gaps and complexities illuminated by earlier research. This research sought to investigate the electrical performance of welded joints connecting battery cell tabs and busbars, with a focus on dissimilar material combinations that are pivotal for battery pack integrity. results demonstrate that while an increase in current passing through the welded joint leads to higher resistance, the magnitude of this increase remains within the milliohm range, exerting minimal impact on the overall performance of electric vehicle battery packs. However, a significant temperature rise within the welded joint, driven by resistive heat loss, may adversely affect battery pack efficiency. Through this research, we identified nickel and nickel-plated steel as favourable material combinations for resistance spot welding, aligning with their prevalent use in automotive battery pack applications. This study also addressed the challenge of electrode sticking, resolving it through higher electrode force and optimized energy input, a problem previously noted by (Ely and Zhou, 2001). It's important to acknowledge the limitations of this study. Notably, this research did not fully explore conductive dissimilar materials such as copper and aluminium, which are increasingly relevant in modern battery pack applications.

6.2 Reliability, validity, sensitivity, and error analysis of the results

In this study, welding tests involving dissimilar materials for battery pack manufacturing were conducted, with a focus on a lap joint configuration using 0.5 mm nickel-plated steel and 0.1 mm nickel strip. The suitability of these materials for welding was determined, leading to systematic studies of nickel-plated steel to Nickel and Nickel to nickel-plated copper pairings. Electrical contact resistance analysis revealed that resistance increased with applied current due to resistive heat loss but remained within a relatively small milliohm range, indicating minimal impact on battery pack performance. Additionally, joint temperature rise was examined, demonstrating that as current increased, temperatures within welded samples also rose, with some samples surpassing the optimal 45°C threshold, potentially affecting battery efficiency. The findings underscored the importance of selecting appropriate pass current values to mitigate adverse temperature effects in battery packs. In evaluating the results, several critical aspects were considered. Reliability was assured through standardized welding procedures and the replication of resistance measurements, ensuring consistent and dependable data. Validity was established by aligning experimental conditions closely with real-world battery pack applications and employing accurate measurement instruments. Sensitivity analysis revealed that while resistance increased with current due to resistive heat loss, the magnitude of this change remained within acceptable limits. Comprehensive error analysis identified minor variations but confirmed that these did not significantly impact the results. Altogether, these assessments attest to the robustness and credibility of the findings, enhancing their overall reliability and validity.

6.3 Conclusion and key finding

The main goal of this research was to investigate the electrical properties, mainly electrical resistance of the welded joint between the battery cell tab and to busbar in a battery pack application in an E-vehicle. There were other objectives also established at the beginning of the research. They are:

- Find out weldability of different dissimilar material combinations by performing initial experiments using resistance spot welding.
- Analyse reliable and effective material combination
- Perform experiment, identify process parameters, and generate weld
- Evaluate electrical performance of welded joints.
- Perform Microanalysis of welded joint
- To analyse, discuss, and interpret results achieved from welding of two dissimilar material.

This thesis achieved all the objectives established at the beginning of this research. This literature review reveals the challenges of connecting two dissimilar materials for the battery pack application. Moreover, the literature review also describes various welding techniques for joining dissimilar materials in the battery pack application. The resistance spot welding technique was chosen in this research to join the dissimilar materials. It is a cost-effective joining technology widely used in the automobile sector, especially in the E-vehicle application. It is essential that what materials are used in the battery pack application as it significantly affects the overall performance of the battery pack. Therefore, in this spot welding were chosen. After systematically identifying the weldable material combinations, experiments were conducted on the Nickel-to-Nickel plated steel with the variation of the parameters and the weld quality was identified by the Hand pull test (manually). thesis, weldability experiments were done on the different dissimilar material combinations, and practical material combinations (Hilumin and Nickel) for the resistance.

Welding parameters for good welding quality were identified. Which can be shown in the table 21 below.

Table 21. identified optimal parameters for resistance spot welding

Sr. No	Parameters	Limits
1	Welding current	Pulse 1 (200A to 3000A), pulse 2 (3800A to 4000A)
2	Energy	Pulse 1 (10ws), Pulse 2 (150ws)
3	Squeeze time	150ms
4	Hold time	6ms
5	Pre-weld delay	30ms
6	Delay between pulses	20ms

One of the central findings of this study pertains to the electrical contact resistance within welded joints. Our analysis revealed a direct relationship between resistance and applied current, primarily due to resistive heat loss. Importantly, these resistance variations remained within a small milliohm range, signifying minimal impact on battery pack performance. The ability to maintain low resistance levels in the welded joints is pivotal for ensuring efficient electrical connections in battery packs. In addition to these findings, our research also made a significant contribution to understanding the weldability of different dissimilar materials, a crucial factor in designing and manufacturing battery packs.

6.4 Novelty value of the research

Primarily, our investigation delved into the electrical contact resistance of welded joints. While previous research has explored various welding techniques and materials, this study sheds light on the nuanced behaviour of resistance concerning applied current, specifically within the context of 0.5 mm nickel-plated steel (Hilumin) and 0.1 mm nickel strip. The discovery of a direct correlation between these factors, with resistance variations remaining within a small milliohm range, represents a novel insight. Furthermore, the examination of joint temperature rise within welded samples in response to varying currents adds another layer of novelty, especially when considering the use of 0.5 mm nickel-plated steel.

In addition to these novel insights, this research also made significant strides in assessing the weldability of different dissimilar materials, including the 0.5 mm nickel-plated steel. This aspect is a vital consideration in designing robust battery pack connections, and the exploration of suitable material combinations and welding techniques with this thickness.

6.5 Generalization and utilization of the results

One of the key strengths of this study lies in its capacity for generalization. While the research focused on 0.5 mm nickel-plated steel (Hilumin) and 0.1 mm nickel strip, the principles and insights gained are transferable to a wide array of dissimilar material combinations frequently encountered in battery pack applications. The observed correlation between electrical contact resistance and applied current, for example, provides a foundational understanding that can be applied to various material pairs, facilitating informed decision making in the selection of materials for battery connections. This generalizability enhances the applicability of the findings to diverse manufacturing scenarios.

The utilization of these results offers substantial benefits to industries. Battery manufacturers stand to gain from the insights into optimizing electrical efficiency and thermal management in battery packs. By leveraging the knowledge of resistance behaviour and temperature dynamics, manufacturers can enhance the design of battery connections and cooling systems.

In conclusion, the results of this research hold the promise of wide generalization and practical utilization. They offer valuable insights applicable to diverse dissimilar material combinations encountered in battery pack manufacturing.

6.6 Topics for future research

Within the scope of this research, attempts were made to weld highly conductive dissimilar materials, specifically aluminium and copper. However, this endeavour was constrained by the limitations of the available resistive spot-welding equipment. It is noteworthy that there exists a paucity of comprehensive research dedicated to the welding of highly conductive dissimilar materials using resistive spot-welding techniques. Consequently, there is an imperative need for future research initiatives in this domain, driven by the recognition that resistive spot welding represents a cost-effective avenue with the potential to substantially enhance the overall efficiency of battery packs in an economically sustainable manner. Furthermore, it is worth highlighting the scarcity of research pertaining to thicker material combinations within the existing body of knowledge. Therefore, it is incumbent upon the research community to engage in extensive exploration of thicker material welding possibilities. Such research endeavours will contribute significantly to the broader understanding of dissimilar material welding for battery pack applications.

7 Summary

This research successfully achieved all its initial objectives. The investigation began by exploring how to connect different materials for battery packs, ultimately selecting a cost-effective method known as resistance spot welding, commonly employed in electric vehicles.

The process of choosing the right materials for battery packs is pivotal to their overall performance. To this end, research endeavours included experiments to identify suitable material combinations. It was determined that utilizing Hilumin and Nickel yielded favourable results for resistance spot welding. Furthermore, various settings for welding Nickel to Nickel-plated steel were systematically tested to ensure the establishment of robust connections.

The examination extended to the determination of optimal welding settings, revealing a direct relationship between increased electrical current and heightened resistance in the connections. This phenomenon could be attributed to the heat generated during the welding process, subsequently elevating the temperature of the connections. Acknowledging this correlation facilitates the prevention of overheating issues.

In conclusion, this research effectively addressed the issues outlined at the outset of the thesis and successfully achieved its primary objectives. Nonetheless, the field of welding dissimilar materials for battery packs continues to offer opportunities for future research and enhancements.

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