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Research Paper

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Quick Spot-welding In Thin Aluminum Sheets using Induction Heating

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***Abstract*—** Spot welding is a widely popular welding technique with immense applications in the automotive industry. Currently, spot welding is carried out using resistance welding. In the present study, a new approach proposes the use of induction heating to achieve strong and quick spot welds in aluminium specimens due to its excessive use in the automotive industry and body in white to improve vehicle performance and fuel economy. The procedure is accomplished through the heat and hit methodology in the form of a portable stapling device. Varying loads and current settings determine the strength of the weld. This paper also shows the critical assessment of thermal losses and the new developments in heat insulation of mild steel pallets which are used to stamp the aluminium sheets in order to carry out the spot welding.

Keywords—Induction Heating, Spot Welding, Aluminium Sheets, Hot Stamping

I. INTRODUCTION

Spot welding is a versatile joining technique used widely in the automotive industry. Typically, the body of a car has about 5000 spot welds [1]. In view of the cost and the weight of the vehicles, most automotive companies aim at using lighter materials. Hence, aluminium is a suitable choice for manufacturing car parts. Transport alone accounts for 27% of aluminium consumption and is expected to grow over the next few years. Every kilogram of aluminium used in a car body brings down the overall weight by one kilogram. This even leads to a significant cut down in fuel consumption and CO_2 emissions. Moreover, it improves the vehicle's mileage, acceleration, shock absorption, braking and is easier to spot weld as compared to heavier materials [2].

In comparison to resistance spot welding, induction spot welding presents various advantages, which lead to its gaining momentum in the automotive industry. Resistance welding involves passing a current through the work piece, the resistance offered by the material will lead to heating and eventually melting. When the material melts, the current stops flowing and hence welding takes place. This approach however requires large amounts of current to be used especially if the metal to be welded (ex: Aluminium) has high conductivity which results in lower efficiency, whereas induction spot welding requires less electricity and is, therefore, an economical choice for the manufacturing units [3]. Furthermore, passing electricity through delicate components might also lead to damage. Induction spot welding supports a variety of materials including both ferrous and non-ferrous and provides focused heat, localized to a specific area, which leads to higher accuracy.

The primary goal of this research is to reduce the amount of electricity supplied to an even greater extent in order to weld aluminium sheets using induction heating. This can be achieved by using a mild steel block. Low carbon mild steel containing high iron content is classified as ferromagnetic material. Strong magnetic properties, along with high resistivity make it an ideal choice of material for the stamping block. It acts as a heat reservoir when placed in the induction coil, which can later be used to melt the surface in contact when stamped against the aluminium sheet in order to create a spot weld.

In the present study, spot welding of aluminium sheets using induction heating is explored. Section I introduces the need of aluminium in the automotive industry and it is joining techniques. Section II contains previous research work carried out in the similar domain. Section III explains the principle of induction heating. Section IV contains information regarding materials and fabrication to carry out this specific kind of spot welding. Section V contains the effects of pre-treatment of aluminium sheets prior to welding. Section VI contains the research architecture and proposed model. Section VII contains information regarding heat insulation to save energy and the final section VIII delivers a proof of concept in form of calculations. Section IX shows the graphical representation of the results. Finally, section X contains conclusion and future scope.

II. LITERATURE REVIEW

Formability of high strength aluminium alloys: The automotive industry is evolving at a pace higher than ever. In order to comply with the rising safety and environmental regulations, most automakers are aiming at achieving absolute minimum weight to enhance engine performance and reduce carbon footprint. These objectives can be achieved by using high strength aluminium alloys for their phenomenal strength to weight ratio. The existing 5xxx and 6xxx aluminium alloys pose problems for security crash components, making the 7xxx the next potential aluminium series. This comes with an enormous challenge of low formability at room temperature. Regarding the formability of high strength aluminium alloys, Mendiguran et al. [4] studied different technology for stamping such as hot stamping, W-temper and warm forming. A blank is heated during the process of hot stamping to a high temperature (~400^{o}c) and retained at that temperature for about 7 sec in a hot resistance furnace before transferring and forcing the blank on the die, post that the die is closed to cool down in a compact environment. They also analysed the metrology inspection report of the hot stamped components and their final material properties. They concluded that hot stamping is a more efficient process of formability since it showed higher geometrical accuracy.

Table 1. Advantages and Disadvantages listed by Mendiguran et al. [4]

Technology	*Advantages*	*Disadvantages*
Hot Stamping	No critical time managing	Bigger process time
W-Temper	Forming is performed at room temperature	Critical time managing, higher tool cost

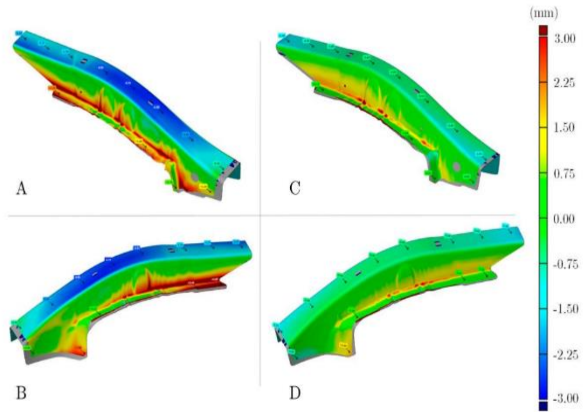

Fig 1. Metrology inspection report: A & B are hot stamped component; C&D are W-Temper component side views by Mendiguran et al. [4]

Hot stamping of high strength aluminium alloy using quick heating: Solution treatment of aluminium alloys is strictly prohibited in critically regulated aircrafts since it causes variations in its mechanical properties. Tomoyoshi et al. [5] have attempted to eliminate cold sizing and the solution treatment from the process of forming high strength aluminium alloys used in aircraft parts. Their study shows the use of furnace and resistance heating of A2024 and A6061 aluminium alloy sheets for drawing and bending operations. They conclude their studies by examining the springback and the strength of the bent T4 sheet. Springback angle turns out to be inversely proportional to the temperature and drops downs almost to zero at 400^{o}C. In addition, the springback of A2024-T4 sheet is greater than that to the A6061-T4 sheet. The graphical representation of the result data gives a clear picture on their relation for bent aluminium alloy sheets under resistance heating.

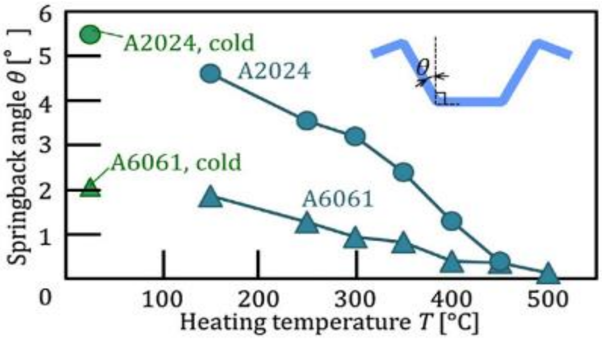

Fig 2. Relationship between springback angle and heating temperature of bent aluminium alloy sheets under resistance heating by Tomoyoshi et al. [5]

On investigating the foregoing research work, we can deduce that resistance heating is widely used for joining and forming purposes. In the present study, we explore the replacement of resistance furnace with induction heating to implement hot stamping. Induction heating is capable of generating immensely high heating temperature in relatively lesser span of time. Hot stamping using induction heating is an efficient process, therefore resulting in not just forming but welding of the thin aluminium sheets.

III. Principles of Inductive Heating

Inductive heating is an energy-efficient method of heating a wide variety of materials in different shapes and sizes. It causes heat generation inside the electrically conductive work piece without any physical contact. The setup consists of an induction coil connected to a high frequency AC source. When the current flows through the coil, it produces an intense alternating electromagnetic field. The temperature of the work piece placed inside the coil increases rapidly due to faraday's law [6]. The frequency of the alternating current regulates the depth of the penetration of the heating effect. High frequency leads to a shallower depth. This phenomenon is known as the skin effect. Since there is no direct contact with the coil, the surface of the work piece remains uncontaminated. Inductive heating shows good reproducibility, prolonged life of fixturing, and favourable compressive residual stresses [7].

IV. Materials and Fabrication

The experimentation was carried out using a multi-turn, single-place copper coil. Due to high coil efficiency and suitability with cylindrical work pieces, a helical coil was employed to use [8]. For scanning or progressive heating, a coupling distance of 0.19 cm is recommended. The aluminium specimens used to carry out the induction spot welding are in form of sheet strips. A cylindrical mild steel block is used for the purpose of stamping after passing it through the induction coil. Table 1 gives the physical properties and dimensions of the materials. The temperature-dependent properties such as thermal conductivity and thermal expansion of the aluminium sheet are shown in Table 2.

Table 2. Physical properties and dimensions of the materials

Parts	*Material*	*Dimensions*	*Specific Heat (J/g°C)*	*Resistivity (Ωm) at 20°C*
Sheet Strips	Aluminium	Length=23.5mm Width=13.2mm Thickness=0.8mm	0.89	2.65×10^{-8}
Coil	Copper	Inner Dia=18mm Outer Dia=20mm No. of Turns=10 Length=74mm	0.385	1.68×10^{-8}
Stamping Block	Mild Steel	Diameter=8mm Length= 80mm	0.5024	10^{10}

Table 3. Temperature dependent properties of aluminium sheets

Temperature (K)	*Thermal Conductivity (W/m.K)*	*Temperature (^{0}C)*	*Thermal Expansion*
300	237	20	1.2e-5
400	240	100	1.33e-5
500	236	300	1.38e-5
600	231	600	1.77e-5
800	218	825	2.06e-5

V. Effects of Pretreatment

The base metal surface used in the process of induction spot welding can impose certain threats on the strength of the weld. This could cause safety and economic failures if neglected. Therefore, pre-treating metals before welding is a necessity to achieve high-quality and long-lasting welds. Surface impurities such as dirt, oil, rust, etc. reduce the effectiveness of the weld, which can lead to disassembling, cleaning, and re-welding the metal. This adds to the already expensive process [9].

Pre-treatment of steel: The surface is first cleaned using acetone solvent to remove dirt or oil. Tools such as sandpaper and angle grinder are used to get rid of stubborn impurities like corrosion or oxidation.

Pre-treatment of aluminium: Aluminium poses greater difficulties in pre-treatments due to its higher thermal conductivity. Initially, it is cleaned using non-chlorinated solvents to remove dirt or grease. Aluminium is highly reactive with oxygen and thus forms an oxide layer quickly. This layer protects it from corrosion but creates problems for welding. Glass blasting is an environmentally friendly method for surface treatment. Apart from this, chemical treatment is carried out using pickling with NaOH to prepare the metal surface for welding [10].

VI. Research Architecture and Proposed Model

The method used for spot welding aluminium sheet strips based on the principles of induction heating consists of three phases (Figure 3). In phase I, power is supplied to the induction module while simultaneously passing the mild steel pallet through the copper coil maintaining an appropriate coupling distance. The gradually progressive heating brings the mild steel pallet to a red-hot state. This is followed by phase II, wherein the hot pallet is hit against the aluminium sheets at the desired location in order to create a spot weld. The time lag between these two phases is kept minimal to avoid heat leakage to the environment. The aluminium sheet strips can also be pre-heated to make the process more efficient. The final stage, phase III, of the mechanism is pressing the mild steel pallet at the spot until the weld cools down to make the weld stronger.

Figure 5 represents the experimental setup used during the process of creating strong spot welds in 0.8mm thick aluminium sheets. The mechanism portrays that of a punching machine. The screw on top drives the dynamic post to facilitate the vertical motion of mild steel pallet. This post is made up of ceramic to reduce heat dissipation and therefore increase the overall process performance.

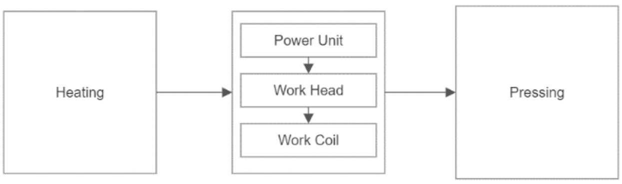

Figure 3. Process mechanism block diagram

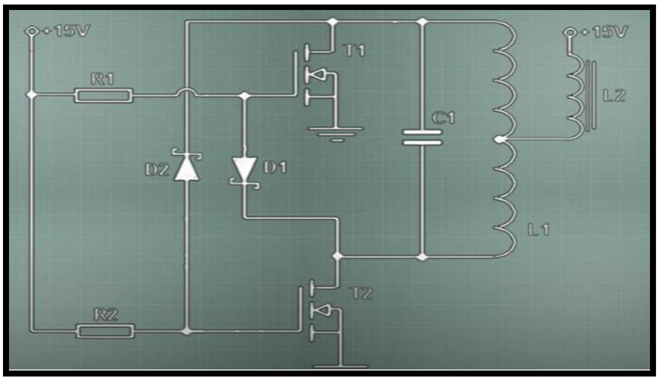

Figure 4. Induction Module Circuit Diagram

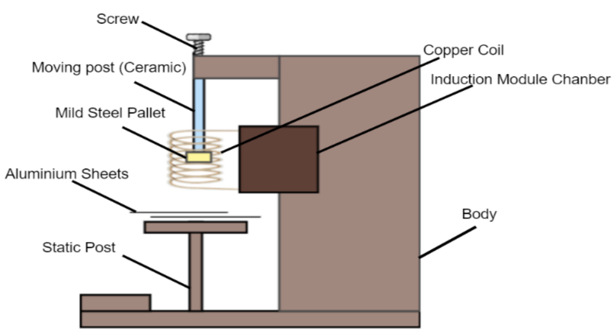

Figure 5. Setup used for experiment of spot welding of aluminum sheets using induction heating

VII. Heat Insulation

The biggest challenge in order to reduce the amount of electricity required to create spot welds is heat loss. The efficiency of this process is inversely proportional to heat dissipation. The two major causes behind higher current consumption are conductive heat losses through aluminium plates and mild steel and radiative heat losses through the air gap between the mild steel pallet and heat insulator [11]. The method adopted to minimize the loss of heat via radiation and conduction is to pack the mild steel pallet with an appropriate insulator while leaving one face open for hitting the aluminium sheet. Table 4 enlists various heat insulators along with their thermal conductivity and maximum withstand temperature. Based on experimental results and thermal analysis, porcelain beads were considered the appropriate choice for heat insulation. The mild steel pallet

Table 4. Properties of various heat insulators

Material	Thermal Conductivity (W/m.K)	Maximum Temperature (°C)	Investigation
Bakelite	0.2	120	Brittle and can darken the object
Teflon	0.250	339	Might melt at a higher temperature, costly
Marble	2.07	600	Heavy, prone to cracks
Cement	1.6	800	Low tensile strength in comparison to weight
Porcelain Beads	0.001	1000	Very high heat insulation, strong

was tightened inside the cut-out made in the porcelain bead according to the dimensions of the pallet in a way that leaves the hitting part of the pallet open for a successful weld. This resulted in a tremendous reduction in the heat lost and made it easier to punch the pallet on the aluminium plate with a better grip.

VIII. Calculation

The heat required to melt the surface of the aluminium sheet strips remotely in order to weld them together is calculated considering external factors of heat loss. The aluminium sheets are assumed to be at room temperature (30°C) before initiating the process. The optimal temperature to which the aluminium sheets must be heated for smooth melting and welding is taken to be 800°C [12]. The calculations are worked out in reverse order to obtain the actual final temperature to which the mild steel pallet must be heated. These results will help us to identify the power required for the induction module. It is notable that this research is based on minimizing the power consumption and hence the equations are derived after close examination of the effects of using porcelain beads as a heat insulator.

A. Heat required by the aluminium plates

$q_{al}= mc\Delta T$

$= 2.7 g/cm^3$

$c = 0.9 J/g^oC$

$m=\delta V$

$m=2.7 g/cc \times\pi\times (0.5)^2 \times 0.08 cc$

$= 0.169 g$

$T = T_f - T_i$

$= 800-30$

$= 770^oC$

$q_{al}= 0.169g\times0.9J/g^0C\times770^0C$

$= 117.56$ J

Qal= 235.129 J

B. Heat Loss

1) Conductive heat loss through aluminium plates

$Q = \lambda A\Delta T$

$= 205 W/mK\times (2\times10)\ cm^2\times770^0C\times10^{-4}$

$= 315.7$ J

2) Conductive heat loss through mild steel

d = 8mm

l = 80mm

$Q = \lambda A\Delta T$

$= 45 W/mK \times (\pi\times\frac{8^2}{4})\ cm^2\times770^0C\times10^{-6}$

$= 1.7416$ J

3) Radiative heat loss through air gap between mild steel and porcelain beads

$Q = A\,(T^4-T_c^{\,4})$

$= 5.6703\times10^{-8} W/m^2K^4\times0.32\times (2\pi\times15\times80\times10^6\times (800^4-30^4))$

$= 140.09$ J

C. Net Heat

Net Heat $= 235.129 + 315.7 + 1.7416 + 140.09$

$= 692.66$ J

D. Heat required by mild steel

$q_{ms}= mc\Delta T$

$m=\delta V$

$m=7.85 g/cc\times (\pi\times\frac{8^2}{4}) \times 0.08 cc$

$= 31.56$ g

$q_{ms}= 31.56g\times0.502J/g^0C\times T$

$= 15.846 J\times T$

On equating,

$692.66 = 15.846\times T$

$T = 43.71^0C$

Final temperature for mild steel $= 800 + T$

$= 843.71^0C$

Heat, $Q = mc\Delta T$

$= 31.56\times0.502 \times (843.71-30)$

$= 12891.705$ J

E. Power

$P = Qt$

$= 12891.705\times15$

$= 859.4 W$

IX. Results

In this work, the main focus lies on saving power while generating high strength weld spots in aluminium sheets. After careful reduction of all possible heat dissipation factors and designing a well-insulated punching machine, the temperature and time of the process was recorded to analyse the overall performance. Quicker the spot welding, higher is its performance capability. The experiment was carried out for different voltage and current iterations i.e. 5V, 9V and 12V and the results are plotted (figure 6). The graph represents the heating time and the temperature of the mild steel pallet. The plot infers that the best results are achieved at 12V with a current of 9A in the induction module. The temperature almost reaches 900^{o}C within a span of 10 seconds. This establishes a strong base for the prospects of induction heating for spot welding.

Apart from heating time and temperature attained, the quality of the weld was also analysed using the universal testing machine. Various stress and shear tests were performed on the specimen post welding. The aluminium sheet strips displayed phenomenally high test results. It could withstand a uni-axial tensile stress up to 200 MPa. The welding process can also be assessed in terms of welding parameters such as power, weld-time, cooling time and weld-pressure. The cooling time of induction spot-welding was recorded to be below 14 sec at room temperature and less than 5 sec in a cryogenic environment.

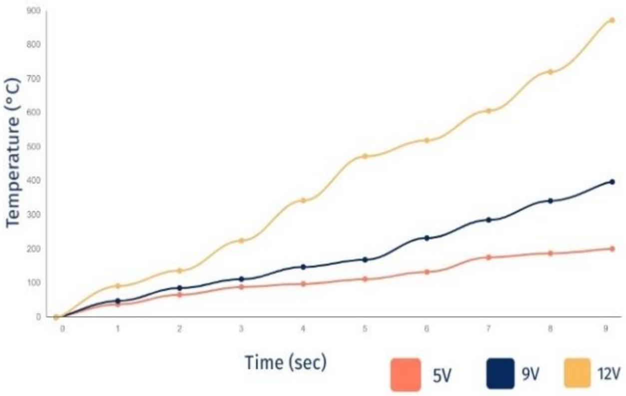

Figure 6. Effect of heating time on the temperature of the mild steel pallet for different voltage iterations

X. Conclusions and Future Scope

The present study deals with the hot stamping of aluminium sheets using a mild steel pallet to create quick and strong spot welds based on the principles of induction heating. The configuration is developed based on the usability of these aluminium sheets in the automotive and aerospace industry. The system is designed considering the thin aluminium sheet required extensively in car parts and aircraft. Basic experiments influence the design of the punching machine and the choice of insulation adopted. The calculations show the optimal power required to carry out welding is less than 1000 W and thus minimizes the wastage. Even though this study reveals how power consumption can be reduced significantly, there is still scope for future work to optimize the efficiency of this process. One major field that needs to be explored to make hot stamping predominant in the automotive and aerospace industry is sheet heating prior to the stamping process. Once the aluminium sheets are treated to make their surfaces ready for welding, they can be heated to the desired temperature. This might have an appreciable impact on the results and performance of the process. Apart from sheet heating, this process can also be customized to be carried out in aluminium alloys as well as hybrid joints. Further investigation and process parameter optimization will lead to revolutionizing the manufacturing industry and replacing resistance spot welding with induction spot welding.

Conflict of Interest

The authors declare that there is no conflicts of interest.

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Author Contribution

Rimpal Jain wrote the manuscript and organized the research work into a draft consisting of tables, graphs and figures. She, also, conducted the statistical analysis of the experimental procedure and drew conclusions based on the results in form of calculations. Dr. C.M. Ramesha made significant contributions in editing and revising the final draft.

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