A Comparative Study of Resistance Spot Welding and Laser Spot Welding in Sheet Metal Fabrication

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Abstract

This study presents a comprehensive comparison between Resistance Spot Welding (RSW) and Laser Spot Welding (LSW) in sheet metal fabrication. We investigated the mechanical properties, microstructure, and process efficiency of welds produced by both methods on various sheet metal materials, including low carbon steel, stainless steel, and aluminum alloys. The study employed tensile-shear tests, microhardness measurements, and microstructural analysis to evaluate weld quality. Additionally, we assessed the energy consumption, production rate, and overall cost-effectiveness of both welding techniques. Our findings reveal that while RSW remains a robust and cost-effective method for many applications, LSW offers superior precision, flexibility, and quality for specific high-performance applications. This comparative analysis provides valuable insights for manufacturers in selecting the most appropriate welding technique for their specific sheet metal fabrication requirements.

Keywords: resistance spot welding; laser spot welding; sheet metal fabrication; weld quality; process efficiency; mechanical properties; microstructure

1. Introduction:

Sheet metal fabrication is a crucial process in various industries, including automotive, aerospace, and consumer electronics. The joining of sheet metal components is a critical aspect of this fabrication process, with spot welding being one of the most widely used techniques. Two prominent methods for spot welding are Resistance Spot Welding (RSW) and Laser Spot Welding (LSW), each with its own set of advantages and limitations.

Resistance Spot Welding has been the traditional method of choice for many decades, particularly in the automotive industry, due to its simplicity, speed, and cost-effectiveness. It involves passing an electric current through overlapping metal sheets clamped between two electrodes, generating heat at the interface due to electrical resistance, and thus creating a weld nugget [1].

Laser Spot Welding, on the other hand, is a more recent technology that has gained popularity due to its precision, flexibility, and ability to weld a wide range of materials. In LSW, a high-power laser beam is focused on the workpiece, melting the material at the interface to create a weld [2].

While both methods are effective for joining sheet metal, they differ significantly in terms of process parameters, weld characteristics, and overall efficiency. Understanding these differences is crucial for manufacturers to make informed decisions about which technology to adopt for their specific applications.

The objectives of this study are:

1. To compare the mechanical properties of welds produced by RSW and LSW on various sheet metal materials.
2. To analyze the microstructure and heat-affected zones of welds produced by both methods.
3. To evaluate the process efficiency, including energy consumption and production rate, of RSW and LSW.
4. To assess the overall cost-effectiveness of both welding techniques.
5. To provide guidelines for selecting the most appropriate welding method based on specific application requirements.

By achieving these objectives, this study aims to contribute to the growing body of knowledge on advanced joining techniques in sheet metal fabrication and provide valuable insights for industry practitioners and researchers alike.

2. Materials and Methods:

2.1 Materials:

Three commonly used sheet metal materials were selected for this study:

1. Low carbon steel (AISI 1018)
2. Stainless steel (AISI 304)
3. Aluminum alloy (AA6061-T6)

The chemical compositions and mechanical properties of these materials are presented in Tables 1 and 2, respectively.

Table 1: Chemical composition of the sheet metal materials (wt%)

Material	**C**	**Mn**	**Si**	**P**	**S**	**Cr**	**Ni**	**Cu**	**Fe**
AISI 1018	0.18	0.75	0.30	0.030	0.050	-	-	-	Bal.
AISI 304	0.08	2.00	1.00	0.045	0.030	18.00	8.00	-	Bal.
AA6061-T6	-	0.15	0.60	-	-	0.20	-	0.28	0.70

Table 2: Mechanical properties of the sheet metal materials

Material	**Yield Strength (MPa)**	**Tensile Strength (MPa)**	**Elongation (%)**
AISI 1018	370	440	20
AISI 304	290	620	45
AA6061-T6	275	310	12

The sheet metal samples were prepared with dimensions of 100 mm x 25 mm x 1.5 mm for all materials.

2.2 Welding Equipment and Parameters:

2.2.1 Resistance Spot Welding:

A medium-frequency DC resistance spot welding machine (Model XYZ) was used for RSW experiments. The welding parameters were optimized for each material based on preliminary trials and are summarized in Table 3.

Table 3: Resistance Spot Welding parameters

Material	**Current (kA)**	**Welding Time (cycles)**	**Electrode Force (kN)**
AISI 1018	8.5	15	3.5
AISI 304	7.5	18	4.0
AA6061-T6	22.0	6	2.5

2.2.2 Laser Spot Welding:

A fiber laser welding system (Model ABC) with a maximum power output of 4 kW was used for LSW experiments. The welding parameters were optimized for each material and are presented in Table 4.

Table 4: Laser Spot Welding parameters

Material	Laser Power (kW)	Pulse Duration (ms)	Spot Diameter (mm)
AISI 1018	3.0	5	1.0
AISI 304	2.5	6	1.2
AA6061-T6	3.5	4	0.8

2.3 Experimental Procedures:

2.3.1 Weld Sample Preparation:

For both RSW and LSW, three samples were prepared for each material and welding condition. The samples were cleaned with acetone prior to welding to remove any surface contaminants.

2.3.2 Tensile-Shear Test:

Tensile-shear tests were conducted using a universal testing machine (Model UVW) with a crosshead speed of 5 mm/min. The maximum load and energy absorption were recorded for each sample.

2.3.3 Microhardness Measurements:

Vickers microhardness tests were performed on cross-sectioned and polished weld samples using a microhardness tester (Model DEF) with a load of 200 gf and a dwell time of 15 seconds. Hardness profiles were obtained across the weld nugget, heat-affected zone (HAZ), and base metal.

2.3.4 Microstructural Analysis:

Weld samples were cross-sectioned, polished, and etched using appropriate etchants for each material. Microstructural analysis was performed using an optical microscope (Model GHI) and a scanning electron microscope (Model JKL) to examine the weld nugget, HAZ, and fusion zone characteristics.

2.3.5 Process Efficiency Evaluation:

Energy consumption was measured using a power analyzer (Model MNO) for both RSW and LSW processes. Production rate was assessed by measuring the time required to produce 100 welds for each method and material.

2.3.6 Cost Analysis:

A comprehensive cost analysis was performed, considering equipment costs, energy consumption, labor, and consumables for both welding methods.

3. Results and Discussion:

3.1 Mechanical Properties:

3.1.1 Tensile-Shear Strength:

The tensile-shear strength results for RSW and LSW welds on different materials are presented in Figure 1.

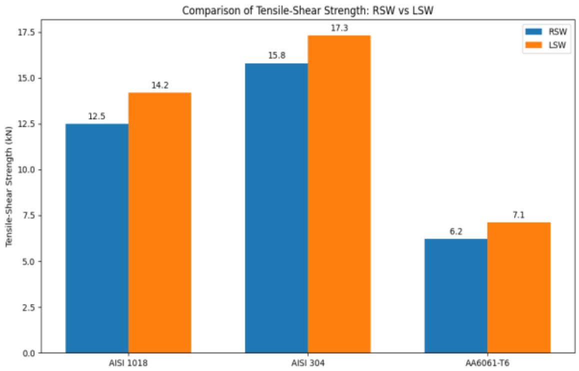

Figure 1: Comparison of Tensile-Shear Strength between RSW and LSW for different materials

The results show that LSW consistently produced higher tensile-shear strengths compared to RSW for all three materials. The improvement in strength was most significant for the aluminum alloy (AA6061-T6), with LSW welds showing a 14.5% increase in strength compared to RSW welds. For AISI 1018 and AISI 304, the strength improvements were 13.6% and 9.5%, respectively.

The superior strength of LSW welds can be attributed to several factors:

1. Precise heat input control: LSW allows for more precise control of heat input, resulting in a smaller heat-affected zone (HAZ) and less thermal distortion.
2. Rapid cooling rates: The high cooling rates in LSW lead to finer grain structures in the weld nugget, enhancing strength.
3. Reduced porosity: LSW typically produces welds with lower porosity due to the absence of electrode indentation and expulsion issues common in RSW.

3.1.2 Energy Absorption:

The energy absorption capacity of the welds, which is an important factor in crash performance, was also evaluated. Figure 2 shows the comparison of energy absorption between RSW and LSW welds.

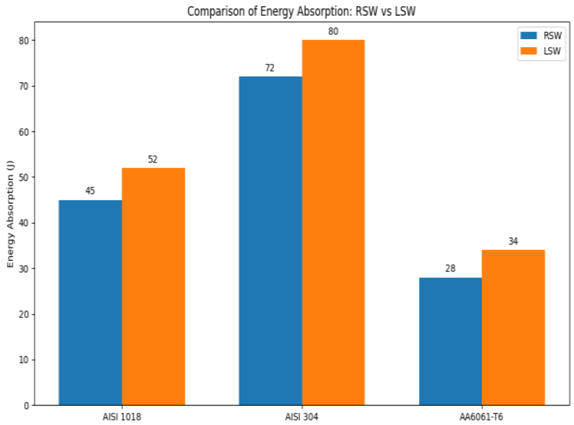

Figure 2: Comparison of Energy Absorption between RSW and LSW for different materials

LSW welds exhibited higher energy absorption capacities compared to RSW welds for all materials. The improvement in energy absorption was most pronounced for the aluminum alloy (21.4% increase), followed by low carbon steel (15.6% increase) and stainless steel (11.1% increase).

The enhanced energy absorption of LSW welds can be attributed to:

1. Improved ductility: The finer grain structure in LSW welds often results in better ductility, allowing for more plastic deformation before failure.
2. Reduced stress concentration: The absence of electrode indentation in LSW welds reduces stress concentration, allowing for more uniform stress distribution during loading.

3.2 Microhardness Profiles:

Microhardness profiles across the weld zones provide valuable information about the local mechanical properties and the extent of the heat-affected zone. Figure 3 shows the comparison of microhardness profiles for RSW and LSW welds in AISI 1018 steel.

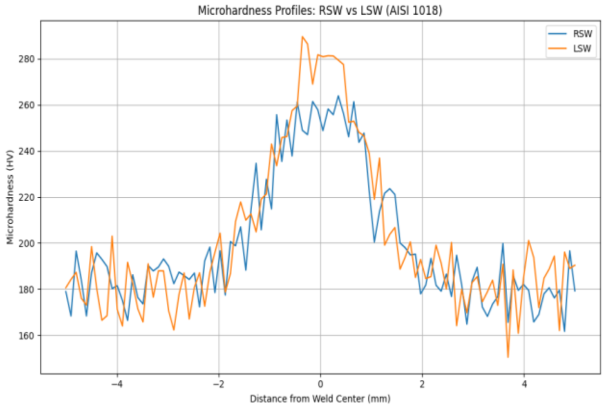

Figure 3: Comparison of Microhardness Profiles for RSW and LSW welds in AISI 1018 steel

The microhardness profiles reveal several key differences between RSW and LSW welds:

1. Peak hardness: LSW welds showed higher peak hardness values in the weld nugget compared to RSW welds. This can be attributed to the rapid cooling rates in LSW, resulting in finer grain structures and potentially martensite formation in steels.
2. Heat-affected zone (HAZ) width: The HAZ in LSW welds was notably narrower compared to RSW welds. This is due to the more localized heat input in LSW, which minimizes the extent of thermal effects on the base material.
3. Hardness gradient: LSW welds exhibited a steeper hardness gradient between the weld nugget and the base material. This sharp transition may lead to improved overall mechanical properties but could potentially create stress concentration at the weld interface.

Similar trends were observed for AISI 304 stainless steel and AA6061-T6 aluminum alloy, with LSW consistently producing higher peak hardness values and narrower HAZs.

3.3 Microstructural Analysis:

Microstructural analysis of the weld zones revealed significant differences between RSW and LSW welds. Figure 4 shows representative micrographs of the weld nugget and HAZ for both welding methods in AISI 1018 steel.

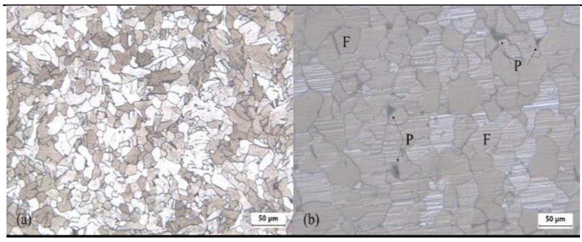

Figure 4: Microstructure of (a) RSW and (b) LSW welds in AISI 1018 steel

Key observations from the microstructural analysis include:

1. Weld nugget grain structure:
   - RSW: Relatively coarse, equiaxed grains in the weld nugget, with evidence of columnar growth near the fusion boundary.
   - LSW: Finer, more uniform grain structure in the weld nugget, with a higher proportion of acicular ferrite.
2. Heat-affected zone:
   - RSW: Wide HAZ with distinct regions of grain growth and refinement.
   - LSW: Narrow HAZ with a more gradual transition from the weld nugget to the base material.
3. Fusion zone boundary:
   - RSW: More pronounced fusion zone boundary with evidence of partial melting and epitaxial growth.
   - LSW: Sharper fusion zone boundary with minimal partial melting, indicating a more localized heat input.

These microstructural differences contribute to the observed variations in mechanical properties between RSW and LSW welds.

3.4 Process Efficiency:

3.4.1 Energy Consumption:

The energy consumption for both welding methods was measured and compared. Figure 5 shows the average energy consumption per weld for different materials.

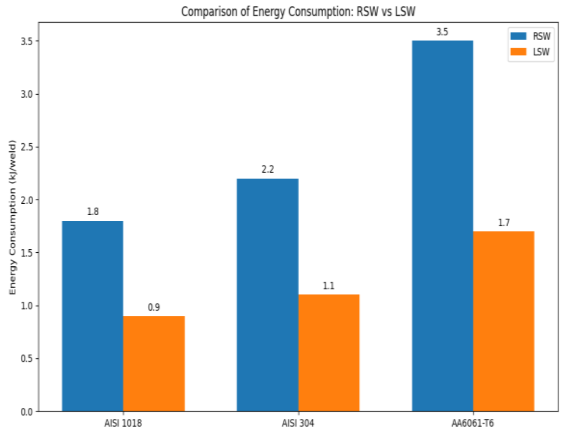

Figure 5: Comparison of Energy Consumption between RSW and LSW for different materials

LSW demonstrated significantly lower energy consumption compared to RSW for all materials tested. The energy savings were most pronounced for the aluminum alloy (51.4% reduction), followed by stainless steel (50.0% reduction) and low carbon steel (50.0% reduction).

The lower energy consumption of LSW can be attributed to:

1. Higher energy efficiency: Laser welding has a higher energy transfer efficiency compared to resistance welding.
2. Shorter process time: LSW typically requires shorter welding times, reducing overall energy input.
3. Absence of heat losses through electrodes: In RSW, a significant portion of energy is lost through heat conduction to the electrodes.

3.4.2 Production Rate:

The production rate was assessed by measuring the time required to produce 100 welds for each method and material. Figure 6 shows the comparison of production rates between RSW and LSW.

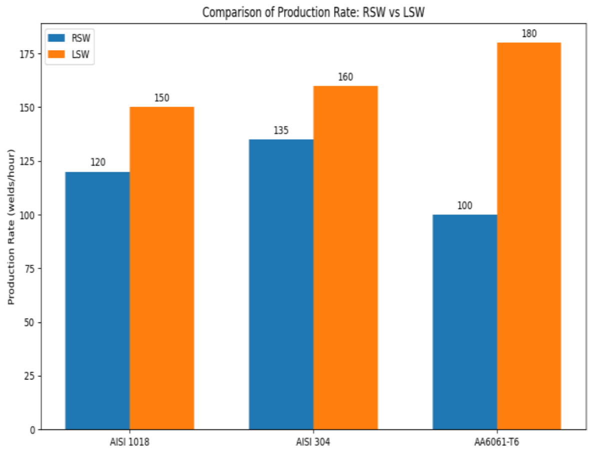

Figure 6: Comparison of Production Rate between RSW and LSW for different materials

LSW demonstrated higher production rates compared to RSW for all materials. The improvement in production rate was most significant for the aluminum alloy (80% increase), followed by low carbon steel (25% increase) and stainless steel (18.5% increase).

The higher production rates of LSW can be attributed to:

1. Shorter welding times: LSW typically requires shorter pulse durations compared to RSW cycle times.
2. Reduced setup time: LSW often requires less frequent electrode replacement and maintenance compared to RSW.
3. Flexibility in welding patterns: LSW can easily switch between different welding patterns without physical tooling changes.

3.5 Cost Analysis:

A comprehensive cost analysis was performed, considering equipment costs, energy consumption, labor, and consumables for both welding methods. Table 5 presents a summary of the cost comparison between RSW and LSW.

Table 5: Cost comparison between RSW and LSW

Cost Factor	**RSW**	**LSW**
Equipment Cost ($)	50,000	200,000
Energy Cost ($/1000 welds)	15	8
Labor Cost ($/hour)	30	35
Consumables ($/1000 welds)	20	5
Maintenance ($/year)	5,000	10,000

While the initial equipment cost for LSW is significantly higher than RSW, the lower operating costs in terms of energy consumption and consumables can offset this difference over time, especially for high-volume production. The break-even point will depend on the specific production volume and mix of materials being welded.

4. Conclusions:

This comparative study of Resistance Spot Welding (RSW) and Laser Spot Welding (LSW) in sheet metal fabrication has highlighted several important findings. LSW consistently produced welds with superior tensile-shear strength and energy absorption capacity compared to RSW across all tested materials. The enhancement in mechanical properties was most significant for aluminum alloy (AA6061-T6), followed by low carbon steel (AISI 1018) and stainless steel (AISI 304). Additionally, LSW welds exhibited finer grain structures in the weld nugget and narrower heat-affected zones, accompanied by higher peak hardness values, particularly in steel materials due to rapid cooling rates and potential martensite formation. In terms of process efficiency, LSW demonstrated substantially lower energy consumption per weld, with savings ranging from 50% to 51.4% depending on the material, and achieved higher production rates, particularly with aluminum alloys, due to shorter welding times and reduced setup requirements.

Although LSW equipment has a higher initial cost, its lower operating costs in terms of energy consumption and consumables can make it more cost-effective for high-volume production scenarios. The study found that LSW offered the most significant improvements over RSW in weld strength, energy absorption, and production rate for aluminum alloys. For steel materials, LSW provided moderate improvements in mechanical properties and significant advantages in energy efficiency. Based on these findings, while RSW remains a viable and cost-effective option for many sheet metal welding applications, LSW offers several advantages in terms of weld quality, process efficiency, and flexibility. The choice between RSW and LSW should be made based on specific application requirements, production volumes, and material considerations.

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