

The Effect of Thread Throat Diameter of Welding Bolt on Weld Defect Formation and its Optimization in Projection Welding

Hilal Kır^{1*}, Mustafa Yazar², Şükrü Talaş³

¹Department of Mechanical Engineering, Faculty of Engineering, Bursa Uludag University, Bursa, Türkiye

²R&D Department, Şahinkul Machine and Spare Parts Manufacturing Co. Ltd., Bursa, Türkiye

³Department of Metallurgical and Materials Engineering, Faculty of Technology, Afyon Kocatepe University, Afyonkarahisar, Türkiye

ABSTRACT

The welding process plays a critical role in the joining of sheet metal parts in the automotive industry, as in other manufacturing sectors. In this study, a welding defect observed in M6x21 weld bolts joined by projection welding—utilizing the protrusion geometry on the fasteners—was investigated. The joining was carried out using 3 mm thick WSS-M1A365-A22 sheet steel and 8.8 grade M6x21 weld bolts; however, insufficient weld strength and low rupture loads were detected. Analytical evaluations revealed that the root cause of the defect was the contact between the bolt geometry and the sheet surface, which caused the welding current to dissipate over a wide area. To eliminate this issue, an M6x26 weld bolt with a smaller thread root diameter and longer thread length was used in the welding process. In order to ensure adequate rupture strength in projection welding with the M6x26 bolt, welding process parameters were investigated. The Taguchi L9 orthogonal array was used to evaluate three different welding currents (26, 28, 30 kA) and three different welding forces (400, 500, 600 daN), with the cycle time kept constant. The rupture load results were analyzed using the “larger-the-better” criterion, and the optimum welding parameters were determined as 600 daN welding force and 30 kA welding current. However, considering energy efficiency in the production environment, it was concluded that a current of 28 kA and a force of 600 daN also provided sufficient weld strength. Scanning Electron Microscope (SEM) analyses enabled microstructural evaluation of weld region defects.

Keywords: Weld bolt, Projection welding, SEM analysis, Taguchi method

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Author Contacts : hilalkir16@gmail.com , mustafa.yazar@sahinkulmakina.com.tr, stalas@aku.edu.tr

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*Corresponding Author

1. Introduction

Projection welding is one of the variations of resistance spot welding, which is widely used in the automotive industry where light weight is important, as in many areas of today's industry [1]. Projection welding, unlike resistance spot welding, transmits the welding current to the contact surfaces through the embossed or machined surface. This limits the projection welding to the contact surfaces and ensures high quality results in the welding processes of fasteners such as nuts, bolts and pins [2]. This situation gains importance due to the fact that most of the joints on the vehicle body are connected with nuts and bolts. In the projection welding process, fasteners such as bolts and nuts have small connection protrusions. During the welding process, the protrusions on the fasteners are pressed on the sheet metal with electrodes and the welding force and welding current in the process are transferred to the sheet metal part. The welding process is completed by forming a welding nugget with the high welding current transmitted to the sheet metal through these protrusions

on the fasteners [3]

Welding processes are affected by many conditions since they depend on various welding parameters such as welding current, compression force process time, material thickness, mechanical and chemical properties of the welding material, environmental factors. Improving the weld quality by analysing the parameters of production processes is closely related to the research and evaluation of welding processes [4,5]. Quality assessments and defects occurring in welding processes are generally performed visually or by non-destructive testing methods [6]. Non-destructive testing tests are applied after the welding process to evaluate the weld quality. These tests detect the source of the defect and ensure that measures are taken to prevent and correct the defect and prevent cost, time and raw material losses [7].

Welding processes are also widely used in the assembly of critical parts. In today's industries, issues such as poor quality problems, reduction of energy consumption and raw material savings are being intensively studied. The most common causes of welding defects are

in compatibility between the base metal and the weld metal, which leads to lack of penetration. The application of the welding process and various welding parameters are some of the other reasons. [8, 9]. Numerous studies on the optimization of welding parameters can be found in the literature. Sharma et al. (2024) conducted a study on the optimisation of Magnesium Inert Gas (MIG) welding parameters using the Taguchi L9 experimental design in combination with the TOPSIS method [10]. Yelamasetti et al. (2024) applied the Taguchi method to the joining of dissimilar metals in Tungsten Inert Gas (TIG) welding. Root gap, welding current, and joint geometry were considered as variable parameters, and the most influential parameter was evaluated based on the output values determined by the ANOVA method [11]. The Taguchi experimental design method has been widely used in welding processes [12-14]. There are also studies in the literature in order to produce production processes with high quality and tolerance values. Li and Simpson (2009) studied out-of-position welding defects on the part in the lap welding process of thin steel plates. They evaluated the welding parameters and discussed the generalisability of the parameters for defect detection. The results showed that some of the parameters studied have potential for defect detection [15].

In this study, the welding defect of an M6x21 weld bolt joined to an automotive sheet metal part by projection resistance welding was investigated. Particular focus was given to insufficient fusion caused by the geometric incompatibility between the welding element (bolt) and the sheet metal, which has been addressed in a limited number of studies in the literature. It was observed that the weld bolt did not join to the sheet metal part and separated under very low tensile forces. In this context, the root causes of the welding defects were investigated in detail and the weld strength was evaluated.

2. Material and Method

Projection welding is generally used in the assembly of welding bolts to automotive sheet metal parts. With projection welding, the welding current and welding force applied on the welding bolt transmit the arc to the sheet metal part through the protrusions on the bolt. With the instantaneous current through the bolt, the protrusions on the bolt perform the melting and solidification processes between the two parts and ensure the completion of the welding process.

In this study, 3 mm thick WSS-M1A365-A22 sheet steel parts are joined by projection welding with 8.8 weld quality W703951/M6x21 reference welding bolt. The technical drawing of the M6x21 welding bolt of 8.8 quality is given in Figure 1.

In the present study, welding processes are carried out with MFDC welding machines under 400, 500 and 600 daN welding compression force and 26, 28 and 30 kA welding current in 1 cycle welding time. In the weld rupture tests carried out to evaluate the weld quality after projection welding, it was observed that the rupture loads were inconsistent and the rupture load dropped below 200 kg. In the rupture tests, some weld bolts broke off from the sheet metal part without any external effect due to insufficient weld strength. Figure 2 shows the sheet metal part whose weld bolt fell off in the rupture test due to insufficient weld strength.



Figure 1. 8.8 W703951/M6x21 welding bolt technical drawing and dimensions



Figure 2. Sheet metal part whose weld bolt falls off due to insufficient weld strength

The root causes of inadequate weld strength were investigated by analysing the results obtained from the weld breaking load tests. In the root cause investigation study, firstly, the joining of 3 mm sheet metal with different welding compression force and welding currents using existing welding bolts was evaluated. It was concluded that the welding parameter values did not improve the weld strength. Upon this result, the geometries of the welding bolt and the sheet metal part were evaluated and their adequacy for the welding process was discussed. During the process analyses, it was concluded that the throat part of the welding bolt's thread bottom was in contact with the sheet metal part, causing the welding flux applied on the bolt to spread over a large area. Figure 3 shows the bolt thread throat. During the process, the bolt thread neck contacts the sheet metal and prevents the welding flux from concentrating on a certain area and sufficient welding strength cannot be achieved due to the end of the process before the welding process is completed. This causes a major problem of poor quality.

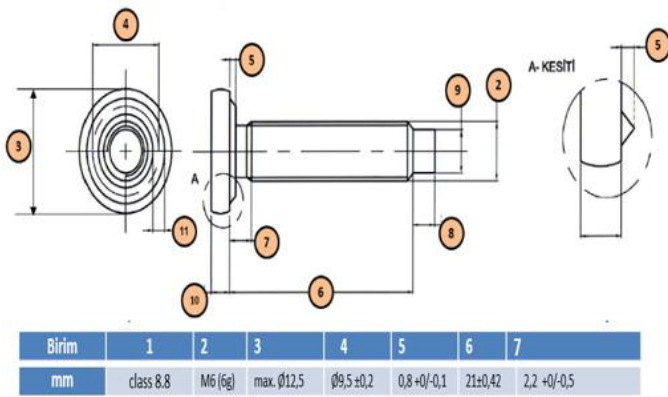


Figure 3. W703951/M6x21 welding bolt thread throat

After the root cause of insufficient weld strength was determined, W703191 / M6x26 welding bolts with smaller thread bottom diameter were used instead of 8.8 quality M6x21 bolt in order to prevent quality problems. This welding bolt was selected with a longer screw height than the M6x21 bolt in order to prevent not only the thread bottom diameter but also the thread heights from contacting the sheet edge. Figure 4.a shows the thread bottom diameters of the M6x21 welding bolt given in the current welding process and Figure 4.b shows the thread bottom diameters of the M6x26 welding bolt studied to improve the weld quality. As shown in Figure 4.a and Figure 4.b, it is concluded that the thread bottom diameter of the M6x26 welding bolt is smaller and does not contact the sheet metal in the welding process and effectively conducts the welding flux on the sheet metal part.

Within the scope of the study, projection welding process parameters of 8.8 grade M6x26 welding bolt with 3 mm thick steel sheet were evaluated. Taguchi method was used for this parametric optimisation problem. Taguchi method is preferred for high quality process optimisation because of its simplicity and low cost [16, 17]. For this reason, experimental analyses were carried out according to Taguchi L9 orthogonal experimental design in order to obtain optimum parameter values. In the experimental study, the effects of 3 different welding compression force (400 daN, 500 daN and 600 daN), 3 different welding current forces (26 kA, 28 kA and 30 kA) on the projection weld rupture load were investigated. In the study, welding time was accepted as 1 cycle as a fixed parameter. The rupture load values obtained were evaluated by S/N (signal to noise ratio) analysis and the results were interpreted.

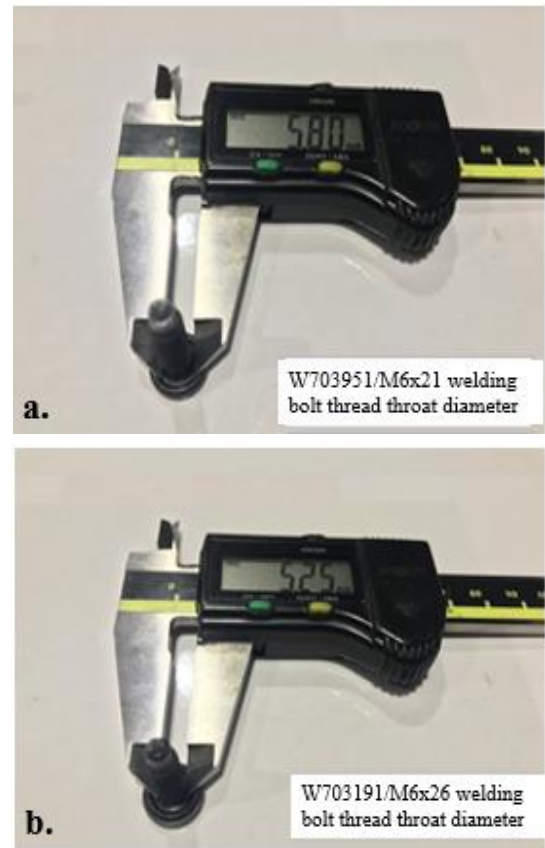


Figure 4.a) M6x21 bolt thread diameter b) M6x26 bolt thread diameter

2.1. Sheet material and welding bolts

The welding bolts used in the welding process are joined to 3 mm thick WSS-M1A365-A22 steel sheet parts by projection welding method. The mechanical and chemical properties of commercially available sheet material are given in Table 1 and Table 2, respectively.

Table 1. WSS-M1A365-A22 sheet material chemical properties [wt%]

C	Si	S	P	Mn	Cr	Ni	Nb
0.07	0.030	0.007	0.018	0.530	0.090	0.090	0.012

Table 2. WSS-M1A365-A22 sheet material mechanical properties

Yield Strength (N/mm ²)	Tensile Strength (N/mm ²)	Elongation (%)
395	466	25.0

The welding bolts used in the study are 8.8 quality. Table 3 shows the mechanical properties of welding bolts with reference numbers W703951/M6x21 and W703191/M6x26 in 8.8 grade.

Table 3. Mechanical properties of welding bolts of grade 8.8

Welding Bolt	Tensile Strength (N/mm ²)	Hardness (HRC)	Elongation (%)
M6x21	872	29	23.0
M6x26	906	27	-

2.2. Welding Parameters

In order to obtain the optimum welding parameters in the projection welding process in which M6x26 welding bolt is joined with 3 mm sheet metal, 3 different welding currents and 3 different welding press forces were studied according to Taguchi L9 experimental design by keeping the welding time constant. Taguchi experimental design parameters are given in Table 4. The values of 26 kA, 28 kA and 30 kA for welding current and 400 daN, 500 daN and 600 daN for welding press forces were investigated.

Table 4. L9 welding parameters and levels

Welding Parameters	Level 1	Level 2	Level 3
Welding Current (kA)	26	28	30
Weld Compression Force (daN)	400	500	600

The experimental parameter ranges were determined according to the welding conditions used in the actual production process of the part, taking into account machine capacity and energy requirements. Therefore, welding compression force between 400–600 daN and welding currents between 26–30 kA were selected. While these values reflect industrial practice, future studies will aim to repeat the experiments with extended parameter ranges to further validate the optimum conditions.

In the study, rupture tests were carried out in order to evaluate the weld quality as a result of the experiments performed according to Taguchi L9 orthogonal test design. The metallographic structures of the rupture specimens obtained from these tests were examined under SEM microscope and the results were interpreted.

3. Results and discussion

Projection welding is one of the most widely used welding processes in the automotive industry, which is generally characterised by high current values in a short time. Projection welding takes place in 4 process steps. These four process steps are the contact of the sheet metal parts or welding elements to be joined by the welding process, the activation energy transferred from the welding robot, the material connection and the holding stage of the samples [18]. During the holding phase of the welding samples, the protrusions on the welding bolt merge with the sheet material and become invisible from the outside. For this reason, the weld quality cannot be evaluated by visual inspection and as a result, weld quality analysis is frequently performed with destructive tests in projection welds [19]. Weld rupture tests are one of the destructive testing methods [20, 21]. In this study, rupture tests were used to evaluate the weld quality. The destructive testing rupture tester operates digitally with a power of 1.5 kW and a load capacity of 20 kN. Figure 5.a shows the tensile test specimens of projection welding of M6x21 sheet metal part and Figure 5.b shows the tensile test specimens of projection welding of M6x26 welding bolt. Figure 6.a shows the thread bottom diameter measurements of M6x21 and M6x26 welding bolts used in these tests under a microscope.

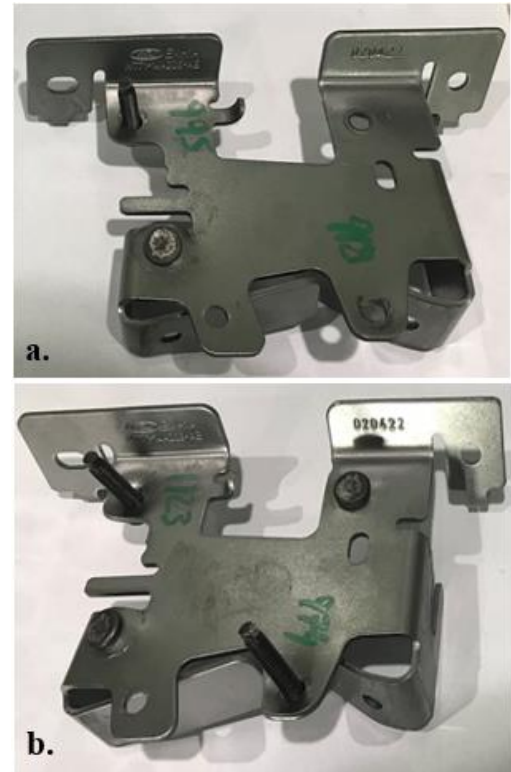


Figure 5.a) M6x21 welding bolt projection weld rupture test b) M6x26 welding bolt projection weld rupture test

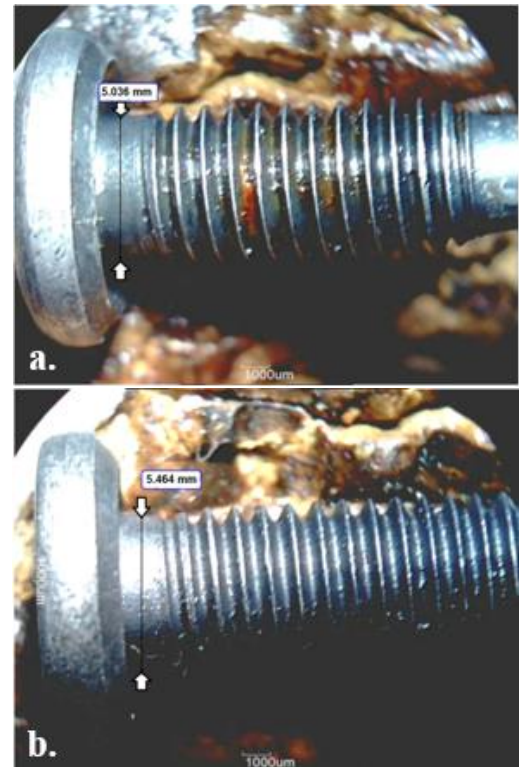


Figure 6.a) M6x21 welding bolt thread bottom diameter b) M6x26 welding bolt thread bottom diameter

In Figure 5a, it was observed that the welding bolt was separated from the sheet metal as a result of the rupture test and the sheet material could not provide sufficient strength. On the other hand, in Figure 5b, it was determined that the M6x26 welding bolt provided

sufficient weld strength due to the sufficient conduction of the welding current to the welding point. Taguchi L9 experimental design was studied for the optimum welding parameter values of the projection welding process using M6x26 welding bolt. For 9 experimental parameters, the results were interpreted according to the S/N (signal to noise) ratio according to the rupture test load values. Taguchi L9 orthogonal experimental design and rupture test results are given in Table 5. Figure 7 shows the S/N graph produced according to the rupture load results.

Table 5. Taguchi L9 orthogonal test design and breaking loads

Experiment No	Welding Current (kA)	Weld Compression Force (daN)	Rupture Load (kg)
1	26	400	87
2	26	500	692
3	26	600	584
4	28	400	547
5	28	500	376
6	28	600	529
7	30	400	433
8	30	500	636
9	30	600	637

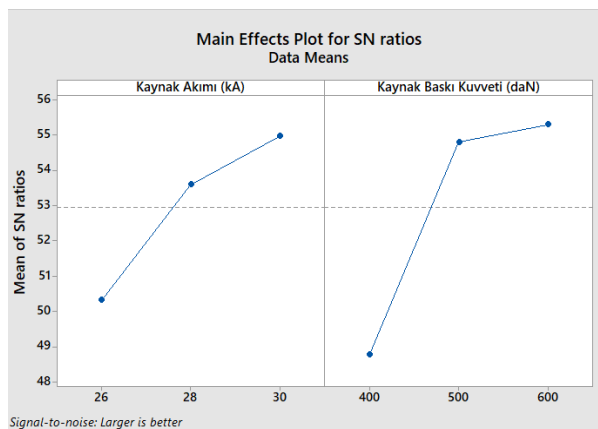


Figure 7. Projection weld rupture analysis S/N graph

The weld rupture strength values obtained in the study were evaluated using the "larger-is-better" method. Accordingly, it is concluded that higher rupture load values provide better weld strength. Although experiment 2 yielded the highest individual rupture load of 692 Kg, Taguchi S/N analysis indicated that this parameter combination was not considered optimum due to lack of consistency and repeatability. Instead, the welding parameters of 30 kA welding current and 600 daN compression force (experiment 9) were determined as the optimum condition, providing both high rupture load and reliable performance. When the breaking load values in Table 5 are examined, it is seen that the lowest breaking load was observed under 400 daN welding compression force and 26 kA welding current. The low value obtained in experiment 1 also influenced the overall reliability of the test results. Figure 8 shows the specimen images examined under SEM microscope after the rupture test.

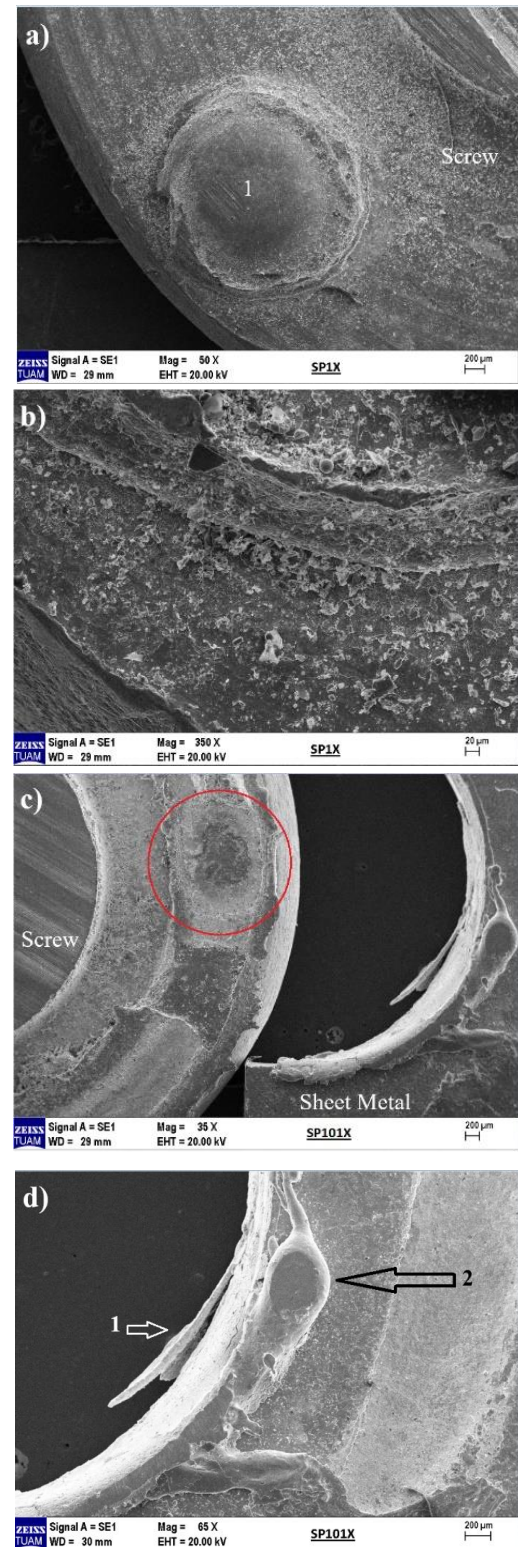


Figure 8. SEM images of failed joint and base metal; a) The welded protrusion on the screw b) the edges of weld protrusion that joined onto the sheet metal c) the failed weld region d) failed flash weld joint showing irregular solidification and molten and solidified metal formed during the welding process

Figure 8 shows protrusion on the screws and failed edges and joints that are subjected to rupture tests analysed under SEM microscope. Figure 8a shows the unwelded protrusion (indicated as 1 on the image) on the screw and the edges. The image suggests that the protrusion was not effectively welded as it has a flat joint surface with finely scattered spatters around the edges. The condition of edges indicate that the failure occurred only on the edges and during the flash weld there was a partial melting at certain places. In Figure 8b, the failed weld protrusion region shown by red circle on the screw indicates an expected failure mode, which was failed normally by the rupture and the opposite part could be located on the sheet metal. This type of failure is normal rupture mode for flash spot welding process. In Figure 8c, the failed screw and sheet metal edge is shown at lower magnification, showing the sheet metal edges that were not supposed to be in contact with the screw head but there is a substantial damage to the edges of the sheet metal and melting of the edges are clearly seen on the surface and ruptured regions where failure is occurred along. It is noticeable that the short circuited weld zone is composed of the flakes of oxidized and/or galvanized layer which were ruptured during the pulling tests. As seen in Figure 8d, the short circuited region contains a drop of molten and solidified metal which is believed to have formed during the short, circuit along the edges of sheet metal. There is also a part that extending from the sheet metal which is believed to be result of improper solidification occurred during the welding process.

This study differs from previous projection welding studies in the literature by systematically demonstrating for the first time that the contact between the bolt thread root diameter and the sheet surface leads to short-circuiting. Thus, it is shown that not only process parameters but also the geometry of the fastening element plays a critical role in weld quality.

4. Conclusions

In the welding optimisation study completed within the scope of the study, the energy coming on the welding bolt with the contact of the welding bolt to the sheet is distributed over a wide area. Due to this heat dissipated during welding analysis, sufficient weld strength cannot be achieved. In order to solve this problem, the geometry of the welding bolt was discussed and the effects of welding parameters on the weld strength were evaluated. As a result of the study in which welding process parameters were analysed;

1. The use of M6x26 welding bolts instead of M6x21, improved weld strength eliminating thread sheet contact and ensuring sufficient nugget formation.
2. Taguchi L9 design showed that the optimum parameters were 30 kA welding current and 600 daN compression force, resulting in a rupture load of 637 Kg.
3. These values are 28 kA and 600 daN in the production area due to the high energy used in the welding process where the welding current is 30 kA and 600 daN welding compression force is used. It is concluded that these values provide sufficient welding strength values.
4. SEM analyses revealed failures caused by short-circuiting at sheet edges and improper solidification, confirming the mechanism of weld defects.

As a result of this study, energy efficiency was achieved with opti-

imum parameter values while providing welding strength in the welding process. In future studies, the number of experiments will be increased in order to increase the reliability of the parameters.

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Conflict of Interest Statement

The authors declare that there is no conflict of interest in the study.

CRediT Author Statement

Hilal Kır: Conceptualization, Formal analysis, Investigation, Writing – original draft, **Mustafa Yazar:** Methodology, Project administration, Resources, Validation **Şükrü Talaş:** Formal analysis, Methodology, Supervision, Visualization, Writing - review&editing

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