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Shear strength of ball studs according to the resistance welding conditions & reliability testing based on the weibull distribution function[†]

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Abstract

As a kind of bolt having a spherical head, the ball stud is widely used as part of a ball joint in steering or suspension sys-tems of automobiles. Generally, the production process of ball studs consists of multi-step cold forging and screw making. This study evaluated the shear strength of joints by varying the welding current and welding pressure in the resistance welding of ball studs. The ball was made with SS400, and the stud was made with SCM435. The sample welded at current of 10.3 kA and welding pressure of 367.7 kPa was tested for its shear strength under different cooling methods. The room temperature cooling of the sample was left at about 293 K for 12 hours after heat treatment. The pressurized air cooling of the sample was subjected to a stream of air at pressure of 490 kPa for 7 seconds. Shear strength test was performed at room temperature with speed setting of 5 mm/min. The shear strength was analyzed by Weibull probability distribution. The scale parameter increased with increasing welding current at welding pressure of 367.7 kPa. The shear strength showed the least dispersion and distribution at welding current of 10.3 kA and welding pressure of 367.7 kPa.

Keywords: Ball stud; Resistance welding; Shear stress; Weibull analysis

1. Introduction

Ball stud is a sphere-shaped fastening element for mechanical parts and is used as a component in ball joints. Unlike ordinary bolt fasteners, the ball stud distributes the overloads and over-momentums acting on the mechanical parts through the slippage and rotation of the sphere. It also ensures that the mechanical part can move in multi-directions. Because of this property, the ball stud is widely used in nearly all types of mechanical systems from suspension to steering systems in automobiles [1, 2].

Generally, the manufacturing process of ball stud consists of multi-stage cold forging and threading. Many researchers have conducted research on the process design and mold design. Others have evaluated the mechanical characteristics of ball studs through high-frequency heat treatment. In recent years, the production of ball and stud involved subjecting each to separate heat treatment processes optimized for their respective material [3-6].

In this case, the shear strength of the ball stud must meet the specifications of the production company. This kind of heat treatment has huge impact on the shear strength of the resistance-welded ball stud. In this research, Weibull distribution was used to evaluate the shear strength of the welding junction in a ball stud designed for automobile application and manufactured by resistance welding. The objective was to determine the best condition for resistance welding, thereby ensuring the safety of the mechanical structure [7].

2. Materials and testing method

The ball was made with SS400, and the stud was made with SCM435. Tables 1 and 2 present the chemical and mechanical characteristics of the materials. Prior to heat treatment, the ball was carburized and hardened. The surface hardness was HRc 55~65, and the carburization depth was 1.0~2.0 mm. The stud was hardened and tempered. As for its mechanical characteristics, HRc hardness was 33~37, tensile strength was 560 MPa, and elongation was 22.4 %. The surface of the stud was coated with black-Zn-Ni.

The resistance welding device used in this study was WT70-V-M made by Weltech, and 12 ball studs were welded using the conditions summarized in Table 3. The appearance of the welded ball stud is shown in Fig. 1. The ball stud was welded at the set current and welding pressure levels, and the heat treatment that followed was applied under the same con-

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Table 1. Chemical composition of tested materials (wt. %).

	C	Si	Mn	P	S	Cr	Mo	Ni	Cu	Fe
SCM435	0.36	0.19	0.71	0.014	0.005	0.99	0.18	0.01	0.01	Bal.
SS400	0.18	0.14	0.55	0.025	0.031	-	-	-	-	Bal.

Table 2. Mechanical properties.

	Tensile strength (MPa)	Yield strength (MPa)	Elongation (%)	Hardness (HRC)	Heat treatment
SCM 435	560	-	22.4	33～37	Quenching & temperature (Zn-Ni coating)
SS 400	484	326	29	55～65	Carburizing (1.0～2.0 mm) & quenching

Table 3. Conditions of resistance welding.

Conditions	Current (kA)	Time (Cycle)	Force (kPa)	Cooling
Welding	10.3	10	318.7	Air
			367.7	
			416.8	
			465.8	
	10.0			
	10.3			
	10.6			
	10.9			
	10.3			Compressed air
Heat treatment	9.5	22	367.7	

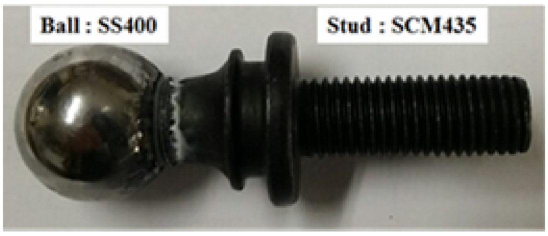


Fig. 1. Appearance of ball stud.

ditions for all current/pressure combinations. In particular, the sample welded at current level of 10.3 kA and welding pressure level of 367.7 kPa was tested for its shear strength under different cooling methods. For room temperature cooling, the sample was left at about 293 K for 12 hours after heat treatment. For pressurized air cooling, the sample was subjected to a stream of air at pressure of 490 kPa for 7 seconds. Shear strength test was performed at room temperature with speed setting of 5 mm/min. The equipment used was NT-502A manufactured by CAS (Inc.). The Weibull probability distribution analysis of the shear strength used 10 data measurement points under each condition. A Rockwell durometer was used for the welded area, and the structure was observed with

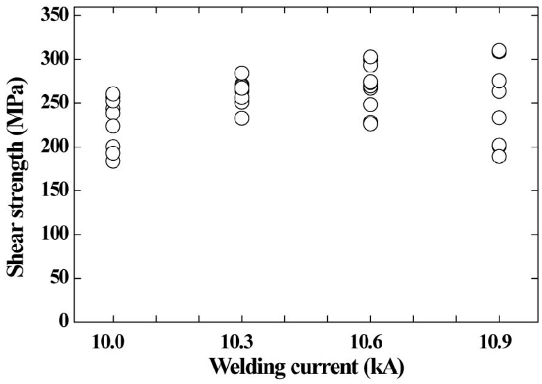


Fig. 2. Shear strength according to welding current under constant welding force (367.7 kPa).

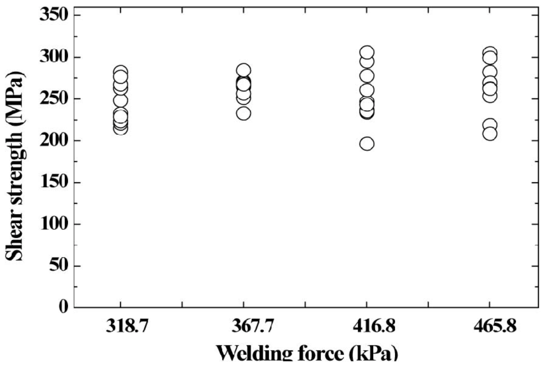


Fig. 3. Shear strength according to welding force under constant welding current (10.3 kA).

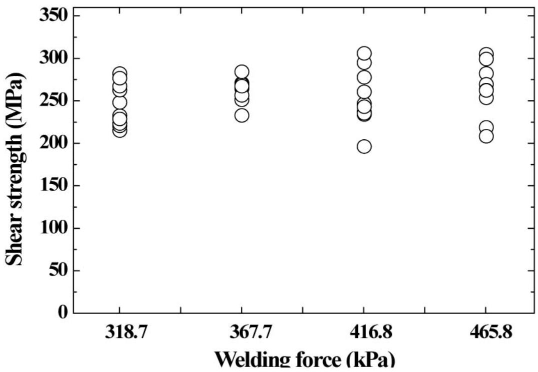


Fig. 4. Shear strength according to cooling type.

a metallurgical microscope. A 1.47 kN load was applied for the Rockwell hardness test. For the observation of the structure, the surface was etched with aqua regia for 5 seconds.

3. Results and review

Figs. 2-4 show the shear stress of the welded sample. Fig. 2 was obtained by varying the welding current levels from 10.0 to 10.9 kA with the welding pressure fixed at 367.7 kPa. Fig. 3 was obtained by varying the welding pressure levels from 318.7 to 465.8 kPa with the welding current fixed at 10.3 kA.

Fig. 4 is the shear stress for various cooling methods (room temperature cooling, compressed air cooling) after welding with current of 10.3 kA and pressure of 367.7 kPa. Room temperature cooling involves leaving the sample at room temperature after welding until the sample cools down. In compressed air cooling, the sample is hit with a stream of air compressed at 490 kPa for 7 seconds and then left at room temperature. The shear stress in the welded samples showed variances depending on the welding current, welding pressure, and type of cooling. The stress measurements were found to have a distribution.

Probabilistic evaluation based on a distribution curve is viewed as increasingly important for improving the accuracy of material strength evaluations. Likewise, in the case of shearing stress, it could be seen that the measurement levels were not constant but had statistical variances. Based on these considerations, for ease of interpretation and to follow the weakest link hypothesis, Weibull statistical analysis was done by applying the 2-parameter Weibull distribution shown below [7].

$$F(x) = 1 - \exp\left[-\left(\frac{x}{\beta}\right)^{\alpha}\right].$$

In this expression, α is a shape parameter representing variations in the probability factor, and β is a scale parameter representing the characteristic lifetime when the probability of malfunction reaches 63.2 %.

Figs. 5-7 are representations of the Weibull probability distribution paper of the shear strength shown in Figs. 2-4, which were measured at the given welding current and welding pressure and cooling method. The data points form a straight line; thus, it can be concluded that the shear stress follows the Weibull probability distribution.

In Fig. 5, the welding current was varied for a given welding pressure (367.7 kPa). At the current level of 10.3 kA, the variances in shear stress were shown to be the smallest. At the lowest current level of 10.0 kA, however, the shear stress distribution was small, and the variances were large. Another observation is that, at higher current levels of 10.6 kA and 10.9 kA, shear stress measurements were higher than at 10.3 kA; at the same time, much lower shear stress measurements were obtained, producing larger variances.

In Fig. 6, the welding pressure was varied for a given welding current (10.3 kA). At pressure level of 367.7 kPa, the variances in shear stress were shown to be the smallest. At welding pressures of 318.7 kPa, 416.7 kPa and 465.8 kPa, however, there were more variances than at pressure of 367.7 kPa. Especially, as the welding pressure increased, more variances were noted in the shear stress measurements.

In Fig. 7, shear stress measurements were obtained for each type of cooling after welding at current of 10.3 kA and pressure of 367.7 kPa. When cooled with compressed air, the measured shear stress had smaller variances than when cooled

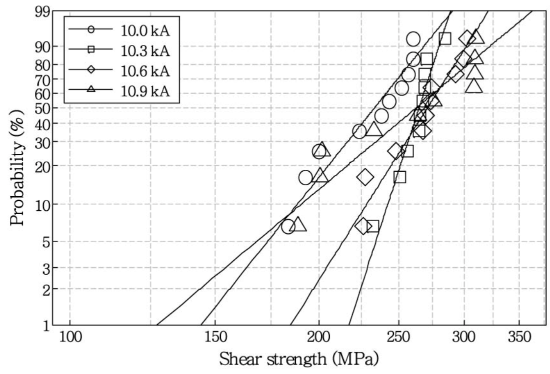


Fig. 5. Weibull probability distribution of shear strength with change of welding current under constant welding force (367.7 kPa).

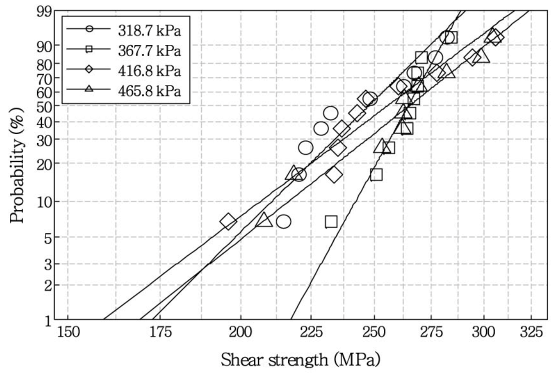


Fig. 6. Weibull probability distribution of shear strength with change of pressing force under constant welding current (10.3 kA).

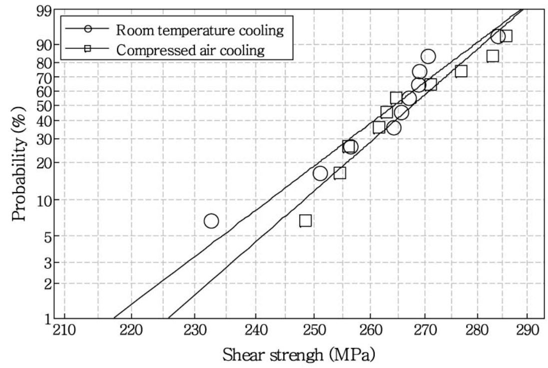


Fig. 7. Weibull probability distribution of shear strength with change of cooling type.

at room temperature, whereas shear strength increased slightly.

Tables 4-6 show the shape parameters and scale parameters of the Weibull distribution function estimated for the shear stress of the welded sample. The standard deviation, mean, and coefficient of variation were also included.

Figs. 8 and 9 are graphical representations of the shape parameters and scale parameters described in Tables 4 and 5. The results in Table 6 are also shown for the comparison of the parameters. The open circle represents the shape parameter, and the solid circle denotes the scale parameter.

Table 4. Estimated Weibull parameters for shear strength according to the change in welding current.

Welding current (kA)	Shape parameter	Scale parameter	Std/mean/COV
10.0	8.7	243.7	29.4/231.3/0.13
10.3	21.6	269.0	13.8/262.9/0.05
10.6	11.1	279.9	27.1/268.3/0.10
10.9	5.9	279.4	50.1/260.1/0.19

Table 5. Estimated Weibull parameters for shear strength according to the change of pressing force.

Welding force (kPa)	Shape parameter	Scale parameter	Std/mean/COV
318.7	11.7	255.5	24.9/245.5/0.10
367.7	21.6	269.0	13.8/262.9/0.05
416.8	8.9	266.2	32.5/253.0/0.13
465.8	9.4	275.4	30.7/262.3/0.12

Table 6. Estimated Weibull parameters for shear strength according to the cooling type under welding current of 10.3 kA and welding force of 367.7 kPa.

Cooling type	Shape parameter	Scale parameter	Std/mean/COV
Room temperature cooling	21.6	269.0	13.7/262.9/0.05
Compressed air cooling	24.8	271.9	12.5/266.5/0.05

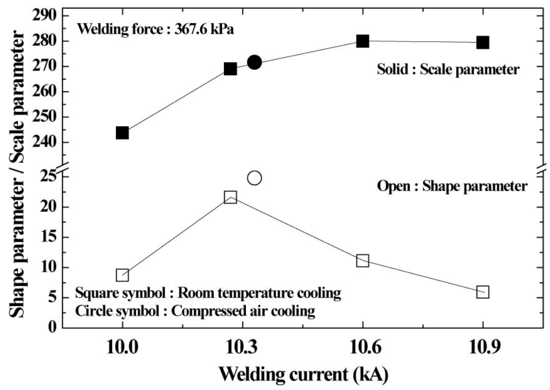


Fig. 8. Shape parameter and scale parameter of Weibull probability from the change of welding current under constant welding force.

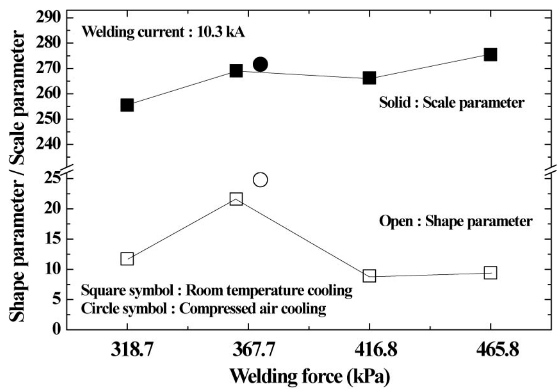


Fig. 9. Shape parameter and scale parameter of Weibull probability from the change of welding force under constant welding current.

Fig. 8 shows the shape and scale parameters when the welding current was varied for a given welding pressure of 367.7 kPa. At current level of 10.3 kA, the shape parameter had the highest value of 21.6. At current levels of 10.0 kA, 10.6 kA and 10.9 kA, however, the shape parameter values were 8.7, 11.1 and 5.9, respectively, which were all less than the value at current level of 10.3 kA. The characteristic lifetime parameter of 63.2 % was found to be 269.0 at current level of 10.3 kA but was at the lower value of 243.7 at 10.0 kA. The other current levels of 10.6 kA and 10.9 kA produced a value of 279.9 and 279.4, respectively; thus suggesting that the scale parameter increases alongside the increase in welding current.

Fig. 9 shows the shape and scale parameters when the welding pressure is varied for a given welding current of 10.3 kA. At pressure level of 367.7 kPa, the shape parameter had the highest value of 21.6. The characteristic lifetime parameter of 63.2 % was found to be 269. At pressure levels of 318.7 kPa, 416.8 kPa and 465.8 kPa, the shape parameter values were 11.7, 8.9 and 9.4, respectively, which were all less than the value at pressure level of 367.7 kPa. The scale parameter at welding pressure level of 465.8 kPa was found to be high at 275.4; at pressure levels of 318.7 kPa and 416.8 kPa, however, the scale parameter values were smaller at 255.5 and 275.4, respectively.

Fig. 10 is a graph of the mean values of shear strength for varying values of the welding current for a given value of welding pressure (367.7 kPa). In the figure, standard deviation is expressed as solid vertical lines. As the welding current increases, the mean shear stress increases until 10.9 kA where it drops.

At welding current level of 10.3 kA, the standard deviation was the smallest at 13.8. The coefficient of variation (COV) at this point was also found to be the smallest at 0.05. The coefficient of variation (COV) at welding current levels of 10.0 kA, 10.6 kA and 10.9 kA were 0.13, 0.10 and 0.19, respectively, which were much larger than at 10.3 kA; thus suggesting large variances.

Fig. 11 is a graph of the mean values of shear strength for varying values of welding pressure for a given value of welding current (10.3 kA). In the figure, the standard deviation is expressed as solid vertical lines. The mean shear strength was at the highest level with 262.9 when welding pressure was 367.7 kPa. The standard deviation was at its smallest value of 13.8 at this point. The coefficient of variation (COV) at this point was 0.05. At welding pressure levels of 318.7 kPa, 416.8 kPa and 465.8 kPa, the mean shear strengths were 245.5, 253.0 and 262.3, respectively, which were all smaller than the mean shear stress at pressure level of 367.7 kPa. The coefficient of variation (COV) at these points was 0.10, 0.13 and

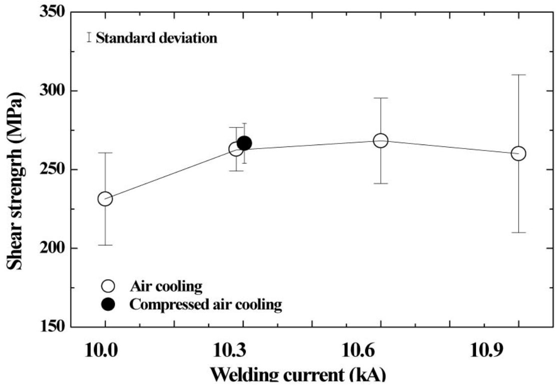


Fig. 10. Shear strength according to welding current under constant welding force.

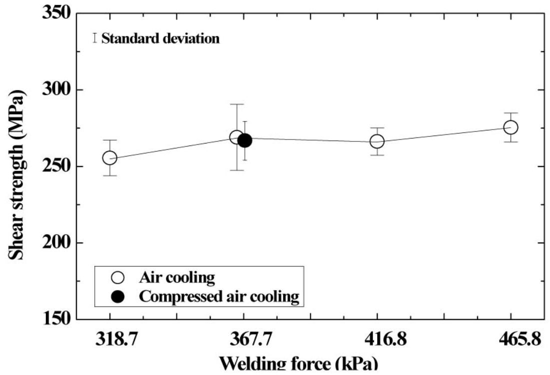


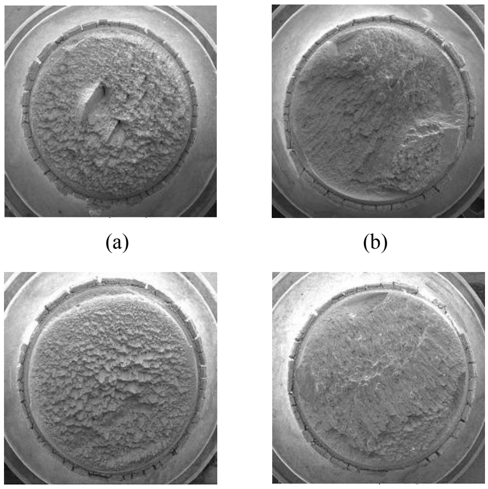
Fig. 11. Shear strength according to welding force under constant welding current.

0.12, respectively, which were much larger than at 367.7 kPa; thus suggesting large variances.

Figs. 10 and 11 display the mean shear strengths for each type of cooling at the welding current level of 10.3 kA and pressure level of 367.7 kPa. The mean values appear slightly larger for compressed air cooling than room temperature cooling.

When the Weibull probability distribution curve, shape and scale parameters, statistical standard deviations, mean, and coefficient of variation (COV) are considered overall, the best condition for welding is produced when the welding current is set at 10.3 kA and the welding pressure is set at 367.7 kPa. Furthermore, after welding under this best condition, compressed air cooling produced higher shear strength than room temperature cooling.

The fractured surface was produced by varying the current while the pressure was fixed at 367.7 kPa during welding and then subjecting the sample to room temperature cooling and compressed air cooling. The fractured surfaces are shown in Figs. 12 and 13. Fig. 12 is the resulting fractured surface after cooling at room temperature, and Fig. 13 is the result after cooling with compressed air. Fig. 12 demonstrates that a uniform shear stress fractured surface is produced regardless of the welding current level. Fig. 13 shows that a uniform fractured surface is also produced when the sample is cooled with compressed air.



(a) (b)

(c) (d)

Fig. 12. Fractured surface by room temperature cooling under different welding current and welding force of 367.7 kPa: (a) 10 kA; (b) 10.3 kA; (c) 10.6 kA; (d) 10.9 kA.

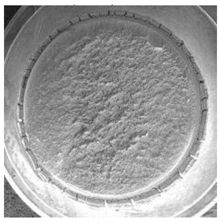
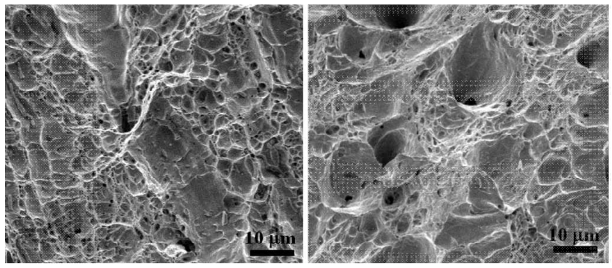


Fig. 13. Fractured surface by compressed air cooling under welding current of 10.3 kA and welding force of 367.7 kPa.



(a) (b)

Fig. 14. SEM fractography of fractured surface with different cooling under welding current of 10.3 kA and welding force of 367.7 kPa: (a) Room temperature cooling; (b) compressed air cooling.

Fig. 14 shows the fractured surface after cooling at room temperature (a) and the fractured surface after cooling in compressed air (b). In both cases, dimples were created, which is evidence of a ductile fracture. Note, however, that the dimples were more prominent in the compressed air cooling case. This could be the reason for the increased shear strength in compressed air cooling. So what follows is that the surface fracturing resulting from room temperature cooling and compressed air cooling is ductile fracturing, with larger dimples produced by compressed air cooling than room temperature cooling; thus leading to higher shear strength.

4. Conclusions

In this research, the shear strength of the welded junction in a ball stud was evaluated by varying the welding current and welding pressure.

The following findings were derived from the research:

(1) The strength when the characteristic lifetime reaches 63.2 % was found to have increased. When the welding pressure level was set at 367.7 kPa and the welding current was increased, the scale parameter increased.

(2) The scale parameter, which represents variance, was measured to be at the 21.6 level when the welding current was 10.3 kA, at which point the variance was at its minimum. Note, however, that the scale parameter values at other current levels were lower with 11.7, 8.9 and 9.4, respectively. These values were corroborated by the larger variances.

(3) Similar results were observed when the welding pressure level was varied with the welding current set at 10.3 kA. Therefore, current level of 10.3 kA and pressure level of 367.7 kPa are the most ideal condition for welding because it produces the most favorable shear strength.

(4) When the shear stress was analyzed after welding at the current level of 10.3 kA and pressure level of 367.7 kPa and then subjecting to different cooling methods, the shear strength was slightly higher when the sample was cooled with compressed air; the variances were also found to be smaller.

(5) The shear strength of the ball stud under all welding conditions met the specification of 1765 kPa. Note, however, that the mean shear strengths of all the welding conditions (with the exception of the optimal condition) had very large standard deviations. It can be concluded that the material was heat-treated unevenly, unless there was a problem with the welding.

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