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ABSTRACT

The effects of lubricant on lap shear strength of Spot Friction Welded (SFW) joints made of 6111-T4 alloys were studied. Taguchi L8 design of experiment methodology was used to determine the lubricant effects. The results showed that the lap shear strength increased by 9.9% when the lubricant was present at the top surface compared to that of the baseline (no lubricant) whereas the lap shear strength reduced by 10.2% and 10.9% when the lubricant was present in the middle and at the bottom surfaces compared to that of the baseline (no lubricant), respectively. The microstructure analysis showed a zigzag interface at the joint between the upper and the lower sheet metal for the baseline specimen, the specimens with the lubricant at the top and at the bottom. However, a straight line interface is exhibited at the joint between the upper and the lower sheet for the specimen with the lubricant in the middle. The weld nugget sizes of the lap shear tested specimens were measured. The nugget size was largest (7.99 mm) for the specimen with lubricant at the top, followed by the base specimens (7.55 mm). The nugget sizes for the specimen with the lubricant at the bottom and with the lubricant in the middle were the smallest (7.31 mm and 7.25 mm respectively).

INTRODUCTION

For a typical automotive body construction, the resistance spot welding (RSW) is a widely used joining technique for sheet metal parts. The RSW process is easy to operate, automate, and control; thereby making it an ideal joining technique for mass production. However, the RSW of aluminum alloys poses some unique problems due to their high thermal and electrical conductivity [1]. These problems include weld porosity, fast electrode wear, and inconsistent failure modes [1-3]. As a result, the automotive industry has switched to structural adhesives, rivets, and toggle-locks to join aluminum panels. Rivets offer better strength and quality compared to RSW [4], but the added material, in turn, adds weight and cost. Adhesives are expensive and require long cycle time for dispensing and curing. Toggle locks are cheaper than RSW, but they are also weaker in fatigue than RSW. Recently, Mazda and Toyota have introduced Spot Friction welding (SFW) technology to join aluminum sheet metal body panels.

SFW is an extension of the very successful Friction Stir Welding (FSW) process used extensively in the aerospace industry for more than ten years to join aluminum alloys. SFW combines friction welding and spot welding together to replace other forms of joining sheet aluminum. This process provides an optimal solution in terms of joint strength, weld quality, investment and operating cost. A schematic illustration of the SFW process joining two metal sheets is shown in Figure 1. A rotating tool with a probe pin is plunged into the upper sheet. When the rotating tool contacts the upper sheet, a downward force is applied. A backing tool beneath the lower sheet is used to support the tool's downward force. The tool's downward force and the rotational speed are maintained for the programmed time (holding time) to generate frictional heat. The heated and softened material adjacent to the tool deforms plastically and a solid state bond is created at the interface of the upper and lower sheets. A typical welded specimen is shown in Figure 2.

Two common types of aluminum sheets used in automotive body construction are: 6xxx series, heat treatable alloys used for parts such as hoods, deck lids and other outer panels, and 5xxx series non-heat treatable alloys used for parts such as latch and hinge reinforcements. These sheets are treated with lubricants at the mill prior to shipping to a stamping facility where the body panels such as hood inner, hood outer etc. are stamped and welded together. The lubricants play an important role during stamping operations. They reduce friction and subsequently lower force and energy requirements while permitting greater deformation. They also help to maintain/improve panel surface quality and improve tool life. There have been many efforts to understand the effects of lubricants in RSW joints and the process parameters to obtain optimal joint strength [5]. Prior work on SFW joint strength did not study in detail the effect of lubricants on the joint strengths. For example, Lin et al. [6, 7] and Arul et al. [8] presented the joint strengths and failure mechanisms under various manufacturing process conditions. Pan et al. [9] and Fujimoto et al. [10] showed the effect of depth of penetration (downward force and hold time) on joint strengths and failure mechanisms.

This study looks at the effects of surface treatment (lubricants) on lap shear strength of SFW joints made of 6111-T4 aluminum alloy.

EXPERIMENTS

Specimen:

Aluminum 6111-T4 sheets with thicknesses of 1.3 mm and 1.5 mm, +0.06 mm/-0.00 mm were used for this investigation. The material was supplied as rectangular panels measuring 308 mm x 1540 mm (12" x 60") with mill applied MP404® surface lubricant. Since this study required precise quantity of lubricants, the mill applied lubricants were first stripped out using acetone and then the sheets were cut into 25.4 mm by 101.6 mm coupons. Then, using an Asymtek® Automove 403 Dispensing system, a prescribed quantity of lubricant was applied with accuracy of ±0.1 g/m^2 for all coupons. Two stamping lubricants were used for this study: Henkel MP-404® representing current production lubricant and Quaker 6130® representing future proposed lubricant for aluminum stamping applications at Ford Motor Company. These lubricants have proprietary ingredients. The toxicology reports indicate that the Henkel MP-404® has the following elements: Petroleum distillates, solvent-refined heavy paraffinic, solvent-refined hydro-treated light paraffinic, and sulfonic acid and the Quaker 6130® has the following elements: Distillates (Petroleum), solvent refined light naphthenic, Petroleum distillates, hydro-treated middle paraffinic, and calcium carbonate.

Design of Experiment (DOE)

A Taguchi L8 orthogonal array matrix is presented in Table 1. Four (4) main variables, three (3) interactions with two (2) states are used. The four main variables and the two states are:

1. A: Lubricant at the top side of the upper sheet metal. The two states (with and without lubricant) are A+ and A- respectively.

2. B: Lubricant at the bottom side of the upper sheet metal. The two states (with and without lubricant) are B+ and B- respectively.

3. C: Lubricant at the top side of the lower sheet metal. The two states (with and without lubricant) are C+ and C- respectively.

4. D: Lubricant at the bottom side of the lower sheet metal. The two states (with and without lubricant) are D+ and D- respectively.

There are a total of eight (8) experiments to complete the Taguchi L8 DOE. The experiments were named as RUN1 through RUN8 as shown in Table 1 and 2. For each experiment, five (5) samples were tested.

SFW Process

The important variables to make SFW joints are: tool geometry, rotational speed, holding time and downward force. The variables within the tool geometry include shoulder diameter, shoulder concavity, pin diameter, pin length, and pin thread pitch. For load-controlled process, the spot friction weld gun can vary the tool rotational speed, holding time, and downward force [11]. For this study, the specimens were prepared with the load-controlled process with the same SFW tool and identical processing conditions.

A Kawasaki® Heavy Industry ZZX 200 robot, D controller, with FSJ option part number 50361-4028 was used for this study. The digitally controlled SFW gun system was equipped with two 3.1 kW servo motors, one controlling the tool rotation via a spindle assembly and the other controlling the axial motion of the spindle. Control of the SFW system was integrated into the robot D controller using a seventh and eighth axis. A fixture was designed to hold two coupons with a steel cover plate. The cover was placed on top of the coupons and tightened using three bolts. The holes on the cover plate provide access to the joining area while preventing a gap between panels.

The specimens were prepared by stacking a 1.3 mm coupon over a 1.5 mm coupon with a 25.4 x 25.4 mm overlap. The coupons were handled carefully not to disturb the applied lubricant around the weld area prior to welding.

Once the specimens were prepared, they were baked at one hundred and sixty five degrees Centigrade (165°C) for twenty (20) minutes to simulate a typical paint baking cycle in automotive assembly plants.

Lap Shear Testing

Lap shear strength is a standardized method of measuring the SFW joint strength. The specimens were tested using an Instron® model 4502 testing machine. The crosshead displacement was set at a rate of 10 mm per minute. No spacer was used during testing to compensate for the offset created by the lap joint. The load and displacement were simultaneously recorded during the test. The tests were terminated when the maximum loads were reached.

RESULTS

The average lap shear strength and standard deviation for each of the eight (8) experiment using Quaker 6130® lubricant and Henkel MP404 lubricant is shown in Table 2. The lap shear strength is the highest for RUN2. The lap shear strength is generally higher when the lubricant is present at the top side of the upper sheet (RUN2, RUN4, and RUN6) compared to that of the baseline (RUN1). The lap shear strength is lower when the lubricant is present between the upper and the lower sheet metal (RUN3, RUN5, and RUN7) compared to that of the baseline (RUN1).

As shown in Table 2, the lap shear strength using Quaker 6130® lubricant and Henkel MP404® lubricant showed same pattern of results and hence further analysis is restricted to Quaker 6130® lubricant.

Using RS-1® statistical tool, the data was analyzed and it was determined that the four (4) main variables (A, B, C, and D) are significant and no interactions exist among them. The effects of A, B, C, and D are shown in Figure 3. For variable A, the average lap shear strength with the lubricant was higher compared to that without the lubricant (4.16kN Vs 3.64kN). However, for variables B through D, the average lap shear strength with the lubricant was lower compared to those without the lubricant (3.8kN Vs 4.01kN, 3.7kN Vs 4.06kN, and 3.76kN Vs 4.05kN, respectively). Based on this, new specimens were prepared with no lubricant (baseline), lubricant at the top (variable A+, i.e., lubricant at the top side of the upper sheet metal), lubricant in the middle (variable B+, i.e., lubricant at the bottom side of the upper sheet metal and variable C+, i.e., lubricant at the top of the lower sheet metal), and the lubricant at the bottom (variable D+, i.e., lubricant at the bottom side of the lower sheet metal). The average lap shear strength for these set of specimens are shown in Table 3. Consistent with the previous results, the average lap shear strength is higher with the lubricant at the top and lower with the lubricant in the middle and at the bottom as compared to that of the baseline.

Figures 4(a)-4(d) show the micrograph of the cross sections of welded samples revealing their microstructures and magnified view of the joint area between the upper and the lower sheet metal for the base specimen (no lubricant), specimen with the lubricant at the top, specimen with the lubricant in the middle, and the specimen with the lubricant at the bottom. The size and shape of the stir zone (light color area around the pin and shoulder) and thermo mechanical affected zone (grey area closely surrounding the stir zone) are similar for all specimens. The joint between the upper and the lower sheet metal forms a zigzag shape for the base specimen, specimen with the lubricant at the top, and the specimen with the lubricant at the bottom. The joint area between the upper and the lower sheet metal is curved up and turns away (hooking) from the pin for the baseline specimen, and the specimen with the lubricant at the bottom. The joint area between the upper and the lower sheet metal is curved up (hooking) and turns toward the pin for the specimen with the lubricant at the top. The joint between the upper and the lower sheet metal show a straight line shape for the specimen with the lubricant in the middle.

Typical weld nuggets after the lap shear tests for the baseline specimen (no lubricant), specimen with lubricant at the top, specimen with lubricant in the middle, and specimen with lubricant at the bottom are shown in Figure 5. The nugget sizes were measured in two (2) different directions for each of the tested specimens. Then, the average nugget size was calculated as shown in Figure 5. The nugget size was the largest (7.99 mm) for the specimens with lubricant at the top, followed by the base specimens (7.55 mm) and then the specimens with lubricant at the bottom (7.31 mm). The nugget size was the smallest (7.25 mm) for the specimens with lubricant in the middle. These results suggest that the nugget size loosely correlates to the lap shear strength.

DISCUSSION

The heat energy generated during the SFW process is transferred into the specimen, the anvil, the tool, and the fixture. The amount of energy transferred depends on the thermal conductivity of each of the material used for specimen, anvil, etc. Su et al. [12] showed that 50% of the heat energy generated transferred into the specimen by using fixture and anvil made of mica, whereas only 12% of the heat energy generated transferred into the specimen if the anvil and fixture were made of steel. When the lubricant was present between the bottom of the lower sheet and anvil, more thermal energy will be transferred to the anvil compared to that of the baseline where air (acts as insulator) is present between the bottom of the lower sheet and anvil.

Su et al. [13] study has shown that the bonded area (or the weld nugget size) positively correlated to lap shear strength and energy into the weld/specimen. Under the same processing condition and using the same tool, it is reasonable to assume that the lubricant between the bottom of the lower sheet metal and anvil would increase the heat transfer to the anvil and reduce the amount of heat energy transferred into the weld compared to that of the baseline. The less heat energy into the specimen will result in a smaller bonded area (or the weld nugget size) and lower lap shear strength compared to baseline, as indicated in Figure 6.

Tozaki et al. [14] and Su et al. [15] have shown that during the SFW process two material flow zone is present: an inner flow zone where the upper sheet material moves downwards with the pin; and an outer flow zone where the lower sheet material moves upwards. This phenomenon will cause the joint area between the upper and lower metal to be curve up and turn away form the pin. This phenomenon is known as "hooking" or "pull-up"[16]. Ikegami et al. [17] showed that a tool with threaded pin produced joint with "hooking" at the interface and had higher strength. Whereas a tool with smooth pin produced joint with no 'hooking' at the interface and had lower joint strength. When the lubricant is present in the middle, it would reduce friction at the interface and hence reduce the tendency of lower sheet material to move upwards. This would decrease the chance of forming "hooking" at the interface, as shown in Figure 4(c). This resulted in lower lap shear strength compared to the baseline.

CONCLUSIONS

The results showed that the lap shear strength is increased by 9.9% when the lubricant is present at the top surface of the upper sheet metal compared to that of the baseline (no lubricant) whereas the lap shear strength reduced by 10.2% and 10.9% when the lubricant is present in the middle and at the bottom surfaces compared to that of the baseline (no lubricant) respectively. The microstructure analysis showed that the joint between the upper and lower sheet metal formed a zigzag line for the baseline specimen and specimens with the lubricant present at the top and at the bottom. However, the joint between the upper and lower sheet metal presented with a straight line for the specimen with the lubricant present in the middle. The nugget sizes of the lap shear tested specimens were measured with the size is the largest (7.99 mm) being the specimen with lubricant at the top, followed by the base specimen (7.55 mm). The nugget sizes for the specimens with lubricant at the bottom and with lubricant in the middle were the smallest (7.31 mm and 7.25 mm respectively).

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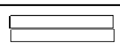
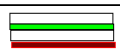
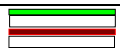
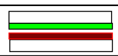
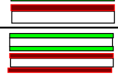
CONTACT

Senthil G. Arul, Body Engineering, Ford Motor Company, Dearborn, MI 48101. Telephone: (313) 805-8107, Email: sarul@ford.com.

Run No	Pictorial representation	Main factor A	Main factor B	Interaction AxB CxD	Main factor C	Interaction AxC BxD	Interaction BxC AxD	Main factor D
RUN1		-	-	+	-	+	+	-
RUN2		+	-	-	-	-	+	+
RUN3		-	+	-	-	+	-	+
RUN4		+	+	+	-	-	-	-
RUN5		-	-	+	+	-	-	+
RUN6		+	-	-	+	+	-	-
RUN7		-	+	-	+	-	+	-
RUN8		+	+	+	+	+	+	+

Lubricant at the top side of the upper sheet metal (with and without lubricant: A+ and A-)
Lubricant at the bottom side of the upper sheet metal (with and without lubricant: B+ and B-)
Lubricant at the top side of the lower sheet metal (with and without lubricant: C+ and C-)
Lubricant at the bottom side of the lower sheet metal (with and without lubricant: D+ and D-)

Table 1
Taguchi L8 experiment set up

Run No	Avg. Lap shear strength with Quaker 6130, kN		Avg. Lap shear strength with Henkel MP404, kN	
	Mean	Standard Deviation	Mean	Standard Deviation
	kN	kN	kN	kN
RUN1	3.94	0.13	4.04	0.09
RUN2	4.51	0.08	4.46	0.10
RUN3	3.52	0.40	3.32	0.15
RUN4	4.27	0.09	4.03	0.22
RUN5	3.37	0.25	3.21	0.18
RUN6	4.23	0.20	4.13	0.18
RUN7	3.75	0.14	3.63	0.22
RUN8	3.64	0.12	3.58	0.38

Table 2
Average lap shear strength and standard deviation using Quaker 6130® lubricant and Henkel MP404 lubricant

Item	Average lap shear strength, kN	Percentage difference compared to baseline
Baseline	3.94	-
Lubricant at the top side	4.33	9.9%
Lubricant in the middle	3.54	-10.2%
Lubricant at the bottom	3.51	-10.9%

Table 3
Average lap shear strength and percentage difference – Baseline, lubricant at the top, lubricant in the middle, and lubricant at the bottom

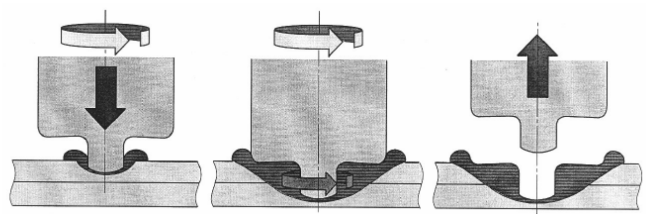


Figure 1
A schematic illustration of spot friction welding (SFW) process

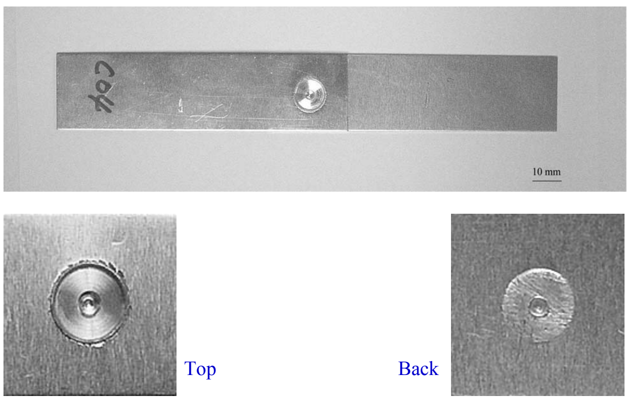


Figure 2
A typical SFW specimen

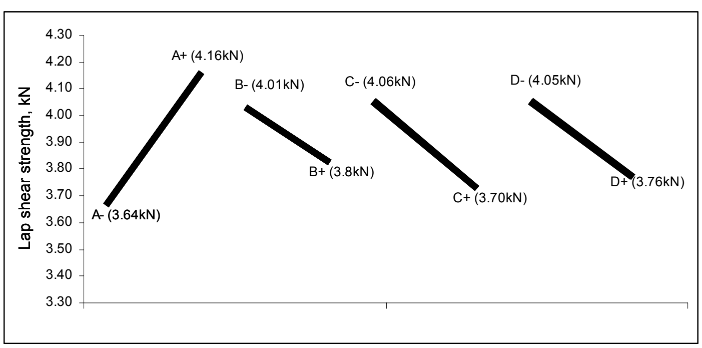
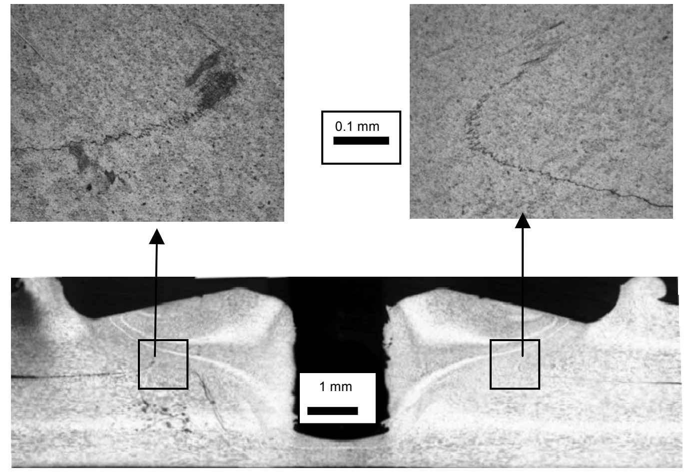
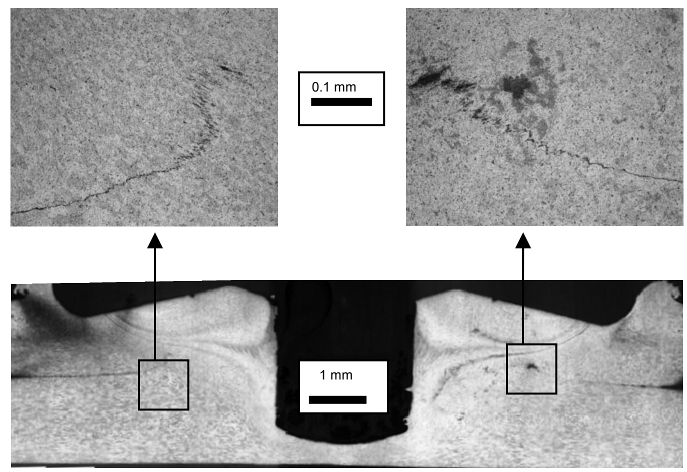


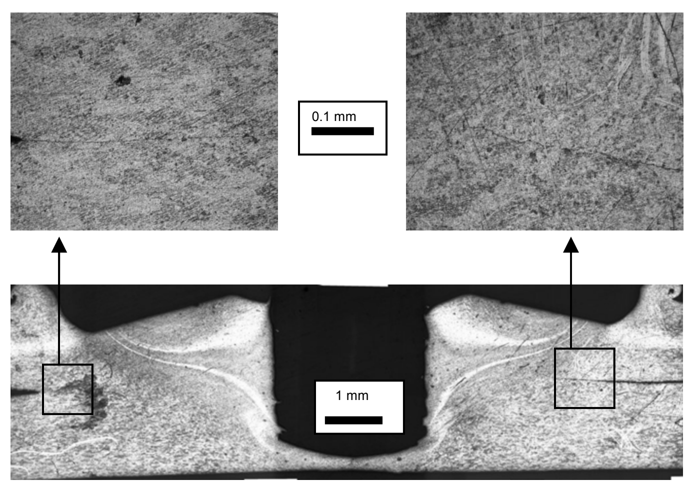
Figure 3
Effect of main factors (A, B, C and D)



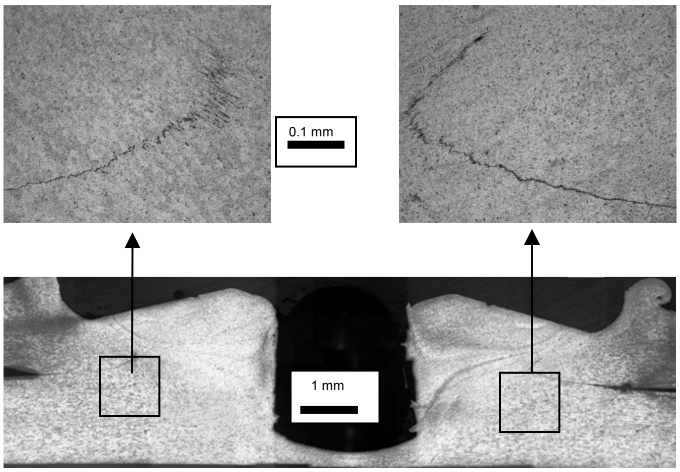
4(a) Baseline – no lubrication



4(b) Lubrication at the top



4(c) Lubrication in the middle



4(d) Lubrication at the bottom

Figure 4(a) - 4(d): Micrographs of the cross section of the SFW joint with the magnified view of the joint between the upper and the lower sheet metal

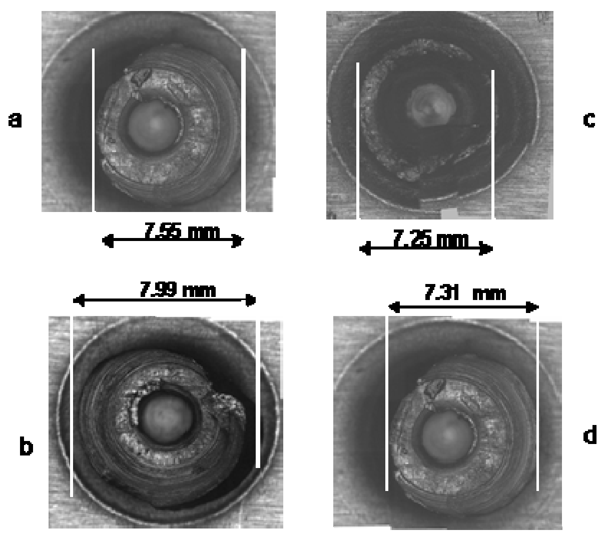


Figure 5
Nugget sizes: (a) Baseline – no lubrication (b) lubrication at the top (c) lubrication in the middle (d) lubrication at the bottom

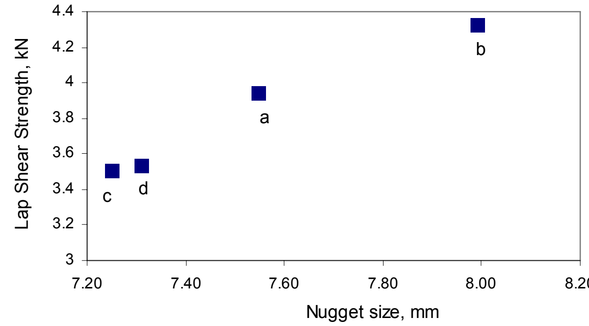


Figure 6
Weld nugget size to lap shear strength relationship
(a) Baseline – no lubrication (b) lubrication at the top (c) lubrication in the middle (d) lubrication at the bottom