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Resistance Welding Parameter Profile for Spot Welding Aluminum

Study shows spot welding characteristics of mill finish 0.036 in. 2036-T4 aluminum

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ABSTRACT. This paper presents the method used and results of a profile study made on the resistance spot welding of mill finish 0.036 in. (0.91 mm) 2036-T4 alloy aluminum. The paper shows the interrelationships and effects of the basic welding parameters, (i.e., current, weld duration and tip force) on the resistance spot welding of 2036-T4 aluminum.

Graphs show three effects. (1) As tip force is increased, there is a larger tolerance in the variation of the otner welding parameters, i.e., current and weld duration where good weld quality is obtained, (2) Longer weld current duration reduces the tendency to have cracks appearing in the sheet under the electrodes, (3) There is a near linear correlation between welding current and weld shear strength which is independent of the number of weld cycles and tip force used.

This study further shows the direction which a welding engineer should take to correct problems encountered in the resistance spot welding of mill finished 2036-T4 aluminum and other aluminum alloys. It also forms a broad reference in the form of welding parameters and resulting data to which other equipment and alloys may be compared.

Introduction

The energy crisis has heightened the automotive industry's efforts to look at new ways to build lighter, more economical vehicles.

Even before the petroleum shortages, automakers were busy meeting Department of Transportation requirements for certain anti-pollution and safety devices on all new automobiles. These devices add weight and operating changes resulting in increased fuel consumption; therefore, the automotive companies are looking for means to offset these weight increases and improve efficiencies. One of these means is through the use of aluminum in both structural and autobody sheet parts. Although some aluminum applications would require heavier gages, others do not. A direct gage for gage substitution of aluminum for steel leads to a 65% weight savings. One of the factors in the reluctance of the automotive industry to incorporate aluminum into cars in the past have been problems related to joining.

In an effort to overcome the joining problem, aluminum producers have developed several new alloys over the past few years which have improved weldability as well as good strength and formability which lend themselves to substitution for steel in sheet metal automobile parts such as hoods, fenders and doors.

In addition, joining process development has taken place to improve resistance spot welding joining methods as they apply to the automotive industries' needs. To improve resistance spot welding joining methods, continuing programs are being conducted by the aluminum industry, welding equipment manufacturers, and the automotive industry. As a part of this work a study was made to determine the interrelationships and effects the basic welding parameters (i.e., current, weld duration and tip force) have on resistance welding of mill finish 2036-T4 aluminum sheet. The results of this study are presented in this paper.

The data compiled during this program were taken from actual welds. Records were kept of current, tip force, weld time and other equipment variables for each individual weld. Physical testing of the welds resulted in the determination of weld strength, button peel, nugget diam-

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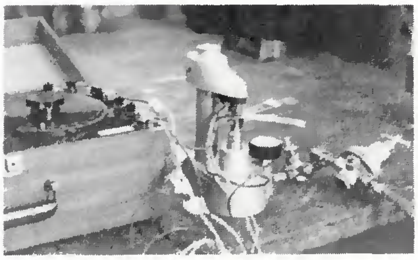

Fig. 1 — Resistance analyzer used to measure surface contact resistance between two sheets of aluminum

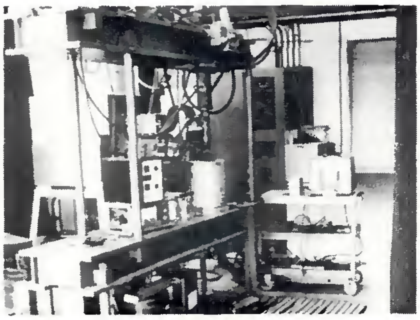

Fig. 2 — The experimental DC resistance spot welding machine on which test welds for the profile study were made

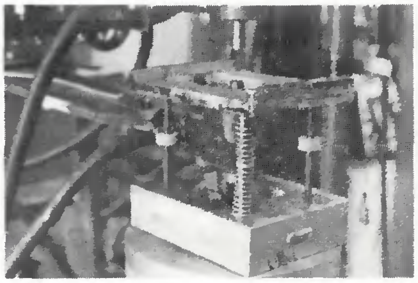

Fig. 3 — Special jig used to locate sample weld coupons

Table 1 — Chemical Analysis Of Material Used In The Profile Study

Element		Wt %
Si	—	0.33
Fe	—	0.27
Cu	—	2.57
Mn	—	0.25
Mg	—	0.45
Cr	—	<0.01
Ni	—	<0.01
Zn	—	0.07
Ti	—	0.04
Al	—	Rem.

eter, weld cracking, porosity, expulsion and surface indentation. With the aid of a computer, these data were analyzed to show the effects of the variables on the quality of the spot welds.

Material

The aluminum used in this study was alloy 2036-T4, 0.036 in. (0.91 mm) gage from one mill-produced lot of material. It was spot welded as received from the production plant. The sheet surfaces had a residual oil which had been applied at the plant to reduce scratching during shipment and handling. No supplemental oil was applied; neither were the surfaces wire brushed or deoxidized.

Surface contact resistance measurements were made on random samples at periodic intervals over the three months it took to complete the tests. These measurements were made by placing two mating sheets of the aluminum between two ⅝ in. (16mm) diameter spot welding electrodes with 3 in. (76 mm) spherical radius contours and applying 600 lb (2670 N) tip force. Resistance was read using a Kelvin Bridge (Ref. 1). The contact resistance measuring equipment is shown in Fig. 1. The average contact resistance was 2000 micro-ohms with individual readings varying from 100 to 9900 micro-ohms.

Specified mechanical properties for 2036-T4 are:

Ult. Str.-42 ksi (29.5 kg/mm^2)
Yield Str.-23 ksi (16.2 kg/mm^2)
Elong. in 2 in. (51 mm) —20%

Chemical analysis of the sheet used in this study is shown in Table 1.

Welding Machine

The study was conducted using an experimental welding machine incorporating a single phase, direct current power supply. The controls were single phase, a cold cathode dekatron heat control with up and down slope and automatic voltage compensation. The welding transformer was rated 100 kVA with a maximum secondary current of 40 kA-RMS.

The welding machine frame was an open window type as shown in Fig. 2. The welding cylinder was double acting with a 3¾ in. (95 mm) bore and 3 in. (76 mm) stroke. The electrodes were Class 1 copper, ⅝ in. (16 mm) diameter with 3 in. (76 mm) spherical radius tips.

Current was measured on the transformer primary and converted to welding current by multiplying it by the transformer turns ratio. The secondary welding heats were measured at the electrode tips by means of an integrating current-resistance-time (IRT) meter. The electrode tip forces were set from a calibration curve for the welding cylinder which related air pressure to tip force.

Welding Procedures and Schedules

The program was set up to determine the interrelationships of the independent variables current, weld duration and tip force on resistance spot weld quality. To accomplish this a total of 135 weld schedules were run in which the tip force was set at four levels of 600, 900, 1200 and 1500 lb, (2670, 4005, 5340, 6675 newtons). Weld duration was set at 1, 3, 5, 8 and 12 cycles. Current was raised by stepping the welding machine phase shift heat control between 40% and 85% of its dial plate markings. Generally six or seven heat settings were used for each tip force and weld duration. This resulted in a current variation from 11 to 45 kA in steps of 3 to 6 kA.

More specifically, the tip force and weld duration in cycles were set at preselected values and the phase shift heat control set at a low heat which resulted in low strength welds. A series would be run with these conditions or schedules. Then in succeeding series the current was usually raised in steps until surface cracks appeared in the sheets or the maximum welding current was reached.

All other welding machine conditions were held constant. Slope control and forge force were not used. Squeeze time and hold time were set at 90 cycles each to allow for stabilization of the system at the time the spot weld was made and kept constant during weld solidification and cool-down. The electrode tips were cooled by 40 F (4.4 C) water flowing at a rate of 1.5 gpm (5.7 lpm) per electrode.

The electrode tips were cleaned at the first sign of tip pick-up using 320 grit emery cloth and a 3 in. (76 mm) spherical radius contoured dressing tool. They were cleaned prior to each series even when no pick-up was evident.

Test Specimens

The welds were made on 4 by 5 in. (102 × 127 mm) coupons positioned in the jig shown in Fig. 3, which overlapped the sheets 1 in. (25.4 mm) and gave a constant spacing of 1 in. between weld centerlines. A series of welds was comprised of 15 welds made with each schedule on three sets of coupons. A nomenclature system was used to identify each series of welds. This system was as follows:

Example: 96B 4
(96) Consecutive series identification numbers — 1 to 135
(B) Test type identification — A, B or C
(4) Number of the spot weld on the coupon

The "A" coupons were sheared into individual 1 in. (25.4 mm) by 7 in. (178 mm) tensile specimens and load tested using a 1000 lb (4450 N) testing machine. The "B" coupons were peel tested and dial calipers used to measure the major and minor button diameters of the peeled weld buttons. The "C" coupons were cross-sectioned, etched and an optical comparator with 10X magnification was used to measure the nugget size, penetration, uniformity and surface indentation of the welds. By the nomenclature it was readily apparent what tests were to be performed on a coupon and easy to tie a weld back to a specific set of welding conditions.

Before destructive testing, all welds were checked for surface cracks using a 20X magnification microscrope. Checks for internal cracks, porosity and expulsion were made by radiographic analysis.

Data Recording

A special data sheet was prepared to make data recording and transfer of the data to a computer as easy as possible. Prior to the start of each series the date, tip force, weld duration, phase shift, water temperature and flow were checked and recorded. As each weld was made the current and IRI meter readings were recorded.

After welding all welds were visually checked for surface cracks and a yes or no recorded on the data sheet. All welds were checked radiographically for internal cracks, porosity and expulsion, and a yes or no recorded at the appropriate place on the data sheet.

As previously indicated, the "A" coupons were load tested and the breaking load in pounds recorded. The "B" coupons were peel tested and it was recorded yes or no as to whether a button was peeled. If a button peeled, the major and minor diameters were measured and recorded. If no button was peeled, zeros were entered for the button diameter. The "C" coupons were cross-sectioned and the weld nugget diameters and penetrations into the sheet measured. Also the surface indentation of the electrode was measured at the centerline of the weld.

There were 114 bits of information recorded or measured for each of the 135 series run. For the whole program there were more than 15,000 bits of information to be sorted, averaged and compared in order to determine the interrelationships of current, tip force and weld duration on spot weld quality. Therefore, a computer was used to expedite data reduction.

Computer Analysis

The information from the data sheets was punched on paper tape and fed into a computer which averaged the current, IRT readings, shear loads, button size, button quality and nugget sizes. It also determined the percentages of button peel, surface cracks, internal cracks, expulsion, weld penetration, porosity and surface indentation. It then printed a table for each series with all the input data, the averages, the percentages, the tip force, weld duration, phase shift, radiograph identification number, surface resistance, water temperature, water flow and series identification.

These printouts gave all the information recorded and calculated for each series of tests. Since the interest was to evaluate the system parameters and not individual welds — and also due to computer core storage limitations, the individual spot weld data were not retained in memory and only the 15 averages — percentages, welding parameters and nugget ovality for each series were saved in the computer memory for further operations.

The computer was programmed to order on demand a particular weld quality in decreasing or increasing order. The first ordering printed out was by series numbers and was used as a summary to plot the various graphs presented.

Computer Results and Discussion

Since the objective of the program was to determine the welding parameters that resulted in good welds, the data was printed based on decreasing values of shear strength. For the 135 series run, the average shear strengths ranged from a high of 822 lb (3658 N) to a low value of 53 lb (236 N). Based on the American Welding Society recommended minimum average strength (AWS-RMAS) (Ref. 2) of 340 lb (1513 N) there were 93 series that met this requirement. These 93 series covered the broad range of welding parameters from 1 to 12 cycles weld duration and 600 to 1500 lb (2670 to 6675 N) tip force. When there was sufficient current, welds with strengths greater than the AWS-RMAS were obtained.

The computer was next asked to order the 93 series by decreasing button peel frequency. There were 75 of the 93 series that met both qualities of AWS minimum average shear strength and 100% peel frequency.

Continuing in this manner, the computer ordered the 75 series by decreasing surface crack frequency, nugget diameter, internal cracking, weld penetration and increasing expulsion. The results of these orderings are shown in Table 2.

As a result of ordering by the cumulative qualities shown in Table 2, series number 57 met all the criteria for spot weld quality. The other 134 series were deficient in one or more of the qualities. Series 57 was run at 900 lb (4005 N) tip force and 27,800 A for eight cycles. The computer data sheet for the fifteen individual spot welds made that comprise series No. 57 is shown in Table 3. Table 2 shows only one way in which the cumulative weld qualities could have been ordered. Other cumulative orderings would give different results.

The cumulative orderings of Table 2 were in the opinion of the authors a logical one in which the most important qualities of shear and button peel frequency were first taken into account. Many times these are the only two qualities which are required of a spot weld and 75 of the weld series met these qualities.

If the welds are to be used where the weld surface appears, either bare or painted, or where there may be a possibility of corrosion, the quality of no surface cracks would need to be taken into account. Of the 88 series which had no surface cracks, 34 met the first two qualities. The other 54 (88 minus 34) series which did not have surface cracks were in general made with low current and exhibited low strength or insufficient peel characteristics.

When the AWS quality of 0.19 in. (4.8 mm) diam buttons (Ref. 2) was applied, 44 of the 135 series met this single quality but only 14 series met the cumulative qualities of shear, peel, no surface cracks and nugget diameter. In this profile study there was a considerable discrepancy in the

Table 2 — Number Of Weld Series Which Meet Certain Weld Quality Standards

Weld Quality	Number of series that met criteria for: Single quality	Cumulative qualities
Shear greater than 340 lbs	93	93
100% button peel	86	75
No surface cracks	88	34
Nuggets greater than 0.19 in. diam	44	14
No internal cracks	76	11
Weld penetration range of 20-80%	111	11
No expulsion	61	1

Table 3 — Computer Data Printout For Series 57

Sample number	Current	IRT meter	Shear load lbs	Peel	Major diam peel, in.	Minor diam peel, in.	Cross sect diam, in.	Surf crack data	Int crack data	Expul data	Penet, %	Poros data	Surf indent, %
57A1	27840	61.4	595					No	No	No		No	
57A2	27968	60.0	525					No	No	No		No	
57A3	27840	59.6	525					No	No	No		No	
57A4	27648	58.9	510					No	No	No		No	
57A5	27520	59.9	510					No	No	No		No	
57B1	27840	59.9		Yes	0.224	0.185		No	No	No		No	
57B2	27648	59.7		Yes	0.219	0.181		No	No	No		No	
57B3	27520	59.6		Yes	0.217	0.191		No	No	No		No	
57B4	27840	59.8		Yes	0.212	0.175		No	No	No		No	
57B5	27840	60.1		Yes	0.209	0.182		No	No	No		No	
57C1	27840	60.8					0.124	No	No	No	49	No	7
57C2	27840	59.0					0.196	No	No	No	42	No	10
57C3	27968	59.2					0.212	No	No	No	59	No	4
57C4	27968	59.6					0.139	No	No	No	42	No	5
57C5	27840	60.4					0.217	No	No	No	69	No	5

Welding parameters for the data shown above

Tip force	900 lb (4005 N)	Temperature water in	40 F (4.4 C)
Weld cycles	8 cycles	Temperature water out	42 F (5.6 C)
Phase shift	60 percent	Flow water top electrode	1.5 gpm (5.68 lpm)
Radiograph ID	5210	Flow water bottom electrode	1.3 gpm (4.92 lpm)
Surface resistance	2830 micro-ohms	AWS minimum shear	270 lb (1202 N)
Nugget ovality	1.18	AWS minimum avg shear	340 lb (1513 N)

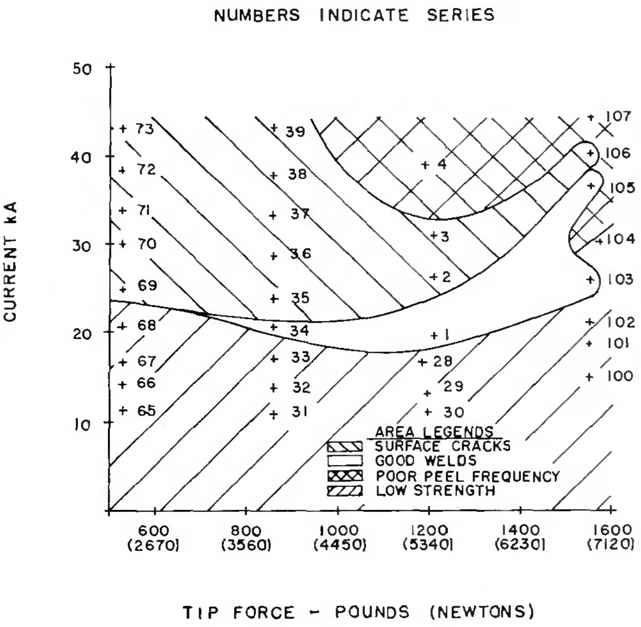

Fig. 4 — Area of good weld parameters; 1 cycle welds

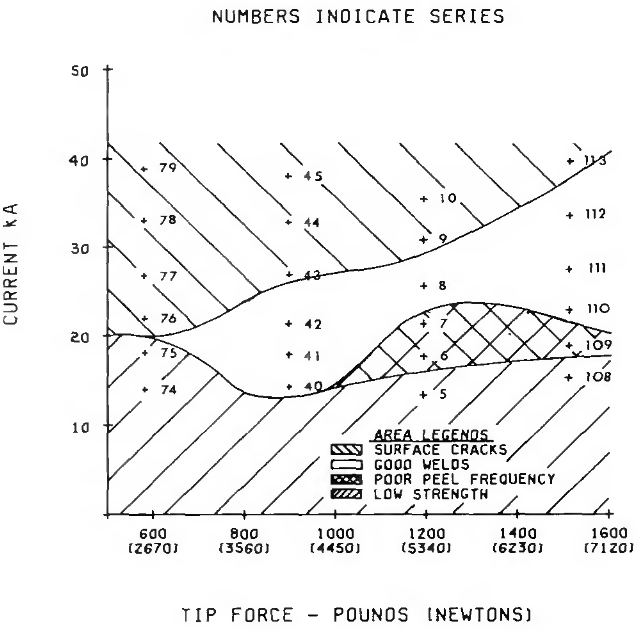

Fig. 5 — Area of good weld parameters; 3 cycle welds

relationship between nugget diameter and shear strength as compared to the relationship published by AWS (Ref. 2).

In this study, 93 series met the AWS-RMAS of 340 lb (1513 N). Of these 93 series, only 44 met the AWS minimum average button size criteria of 0.19 in. (4.8 mm) diam. The profile shear strength for 0.19 in. (4.8 mm) diam buttons was 530 lb (2358 N) and conversely the button size corresponding to 340 lb (1513 N) was 0.135 in. (3.4 mm) diam.

The AWS minimum averages are applied to a broad range of alloys; however, specific applications involving certain alloys may require a readjustment of the AWS Tables to better reflect the button size to strength relationship of spot welds on higher strength aluminum alloys.

Returning to the criteria for measuring weld quality, the next quality considered was internal cracking. There were 76 series with no internal cracks and 11 of these also met the preceding quality requirements.

One hundred eleven (111) series had weld penetrations in the range of 20% to 80% which is the AWS recommended range for weld penetration (Ref. 3). If penetration is greater than 80% there is a tendency toward surface cracking and if the penetration is less than 20% there is a tendency toward a low button peel frequency. The 86 series which peeled 100% buttons showed good correlation with 111 series which had proper weld penetrations. In the cumulative quality check, none of the series were rejected for improper penetration.

As a refinement in the program, the quality of no expulsion was applied to the cumulative quality order and only one weld schedule met this and all previous weld qualities. This was series No. 57 (Table 3).

Series No. 57 had an average shear

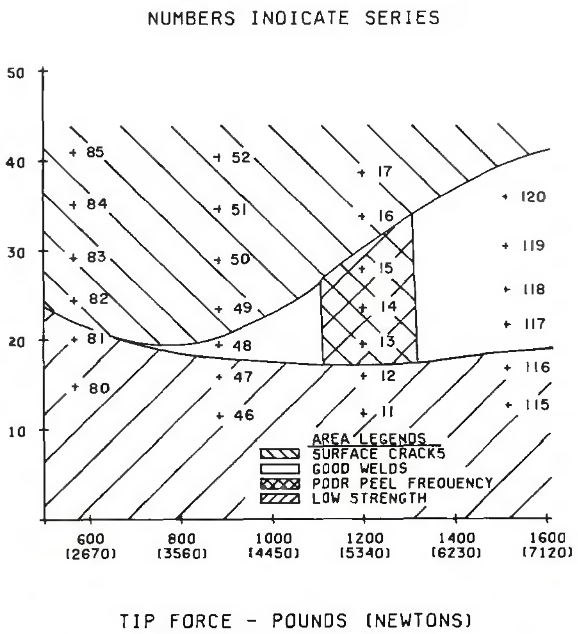

Fig. 6 — Area of good weld parameters; 5 cycle welds

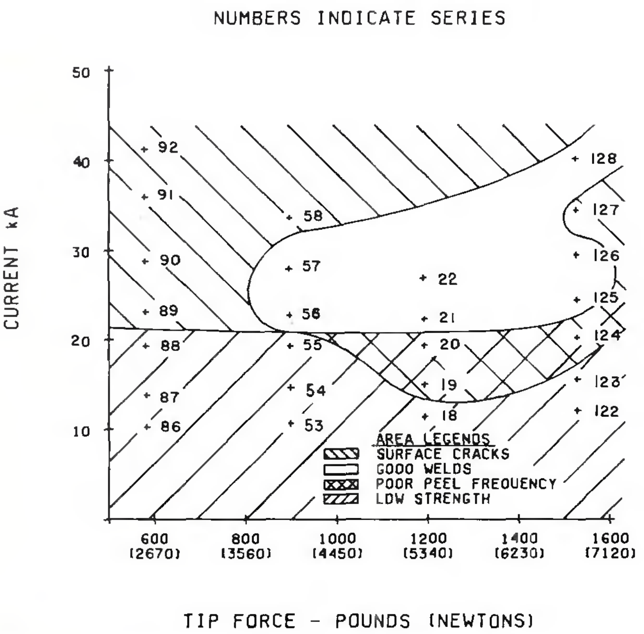

Fig. 7 — Area of good weld parameters; 8 cycle welds

strength of 533 lb (2375 N) a button peel size of 0.199 in. (5 mm) diam, a sectional nugget diam of 0.177 in. (4.5 mm) and a weld penetration of 52%.

Graphic Results and Discussion

To better visualize the relationship between current, tip force and weld duration, plots were made of secondary current versus tip force for a constant number of weld cycles. Figures 4, 5, 6, 7 and 8 show the series numbers for 1, 3, 5, 8 and 12 cycle welds. The series numbers are plotted at their current and tip force coordinates.

In the plots the weld areas are labeled surface cracks, good welds, poor peel frequency and low strength. These areas were defined as shown in Table 4.

Button diameter, internal crack frequency, expulsion and nugget penetrations were not considered for these plots in order to show the interrelationships of shear, peel and surface cracking.

Figure 4 shows that when welds were made with one cycle of current there was only one schedule which resulted in good welds at 900 and 1200 lb (4005 and 4340 N) tip force. At 1500 lb (6675 N) two schedules met the good weld criteria. Series No. 104 failed because one weld did not peel a button. At 600 lb (2670 N) tip force none of the schedules met the criteria for good welds. Series 68 run at 21.3 kA had low weld strength and poor button peel frequency. For series 69 the current was raised to 25.2 kA, and welds with good strength and good button peel frequency resulted, but these had surface cracks. The 1, 3, 5 and 8 cycle welds at 600 lb (2670 N) tip force followed the gen-

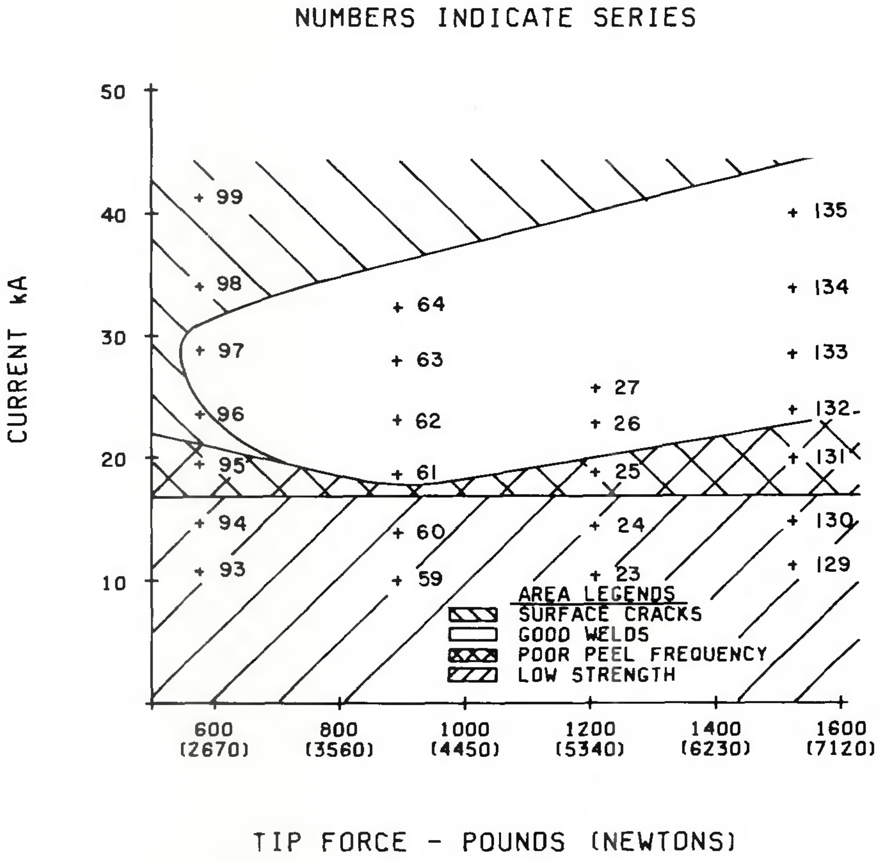

Fig. 8 — Area of good weld parameters; 12 cycle welds

Table 4 — Weld Quality Criteria for Figs. 4, 5, 6, 7 and 8

Condition	Strength greater than AWS-RMAS	Peeled 100% buttons	Had surface cracks
Surface cracks	Yes	Yes	Yes
Good welds	Yes	Yes	No
Poor peel frequency	Yes	No	(a)
Low strength	No	(a)	(a)

(a) Not checked

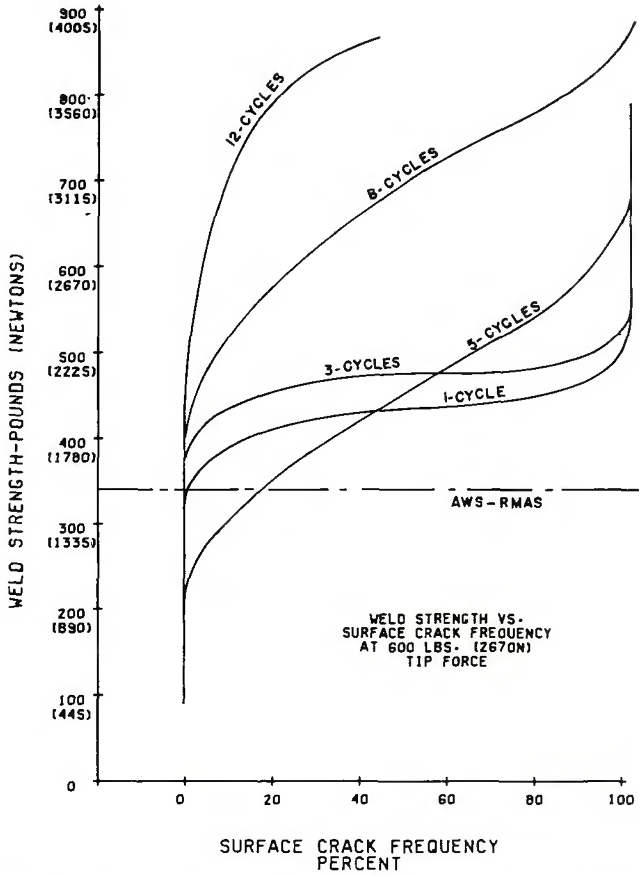

Fig. 9 — Shear strength vs. percentage surface cracks at 600 lb (2670 N) tip force

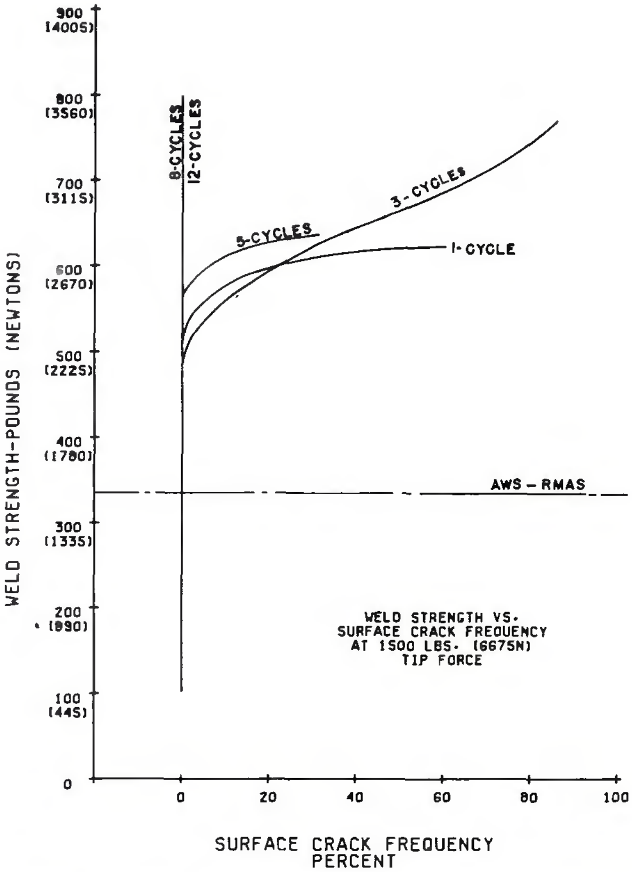

Fig. 10 — Shear strength vs. percentage surface cracks at 1500 lb (6675 N) tip force

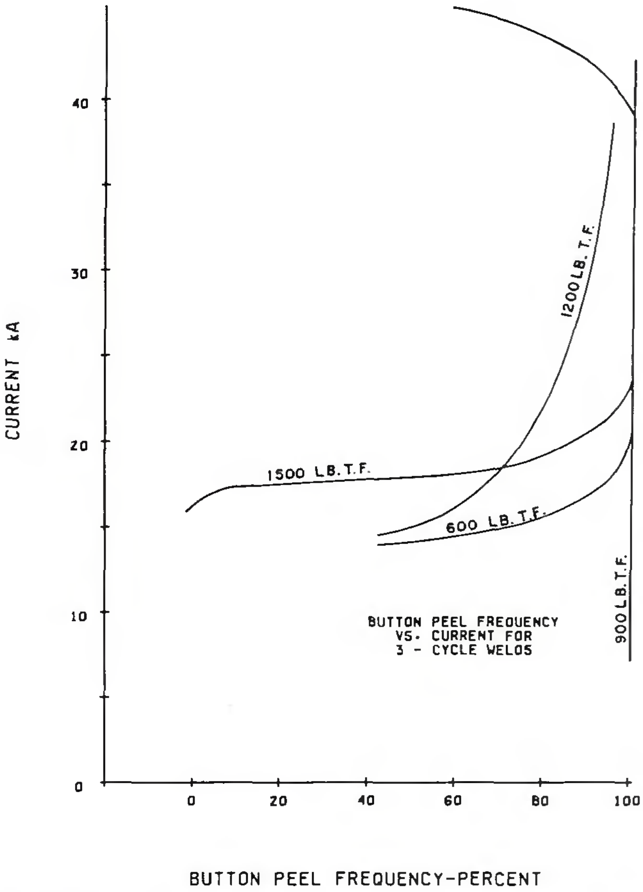

Fig. 11 — Percent peel vs. secondary current for 3 cycle welds

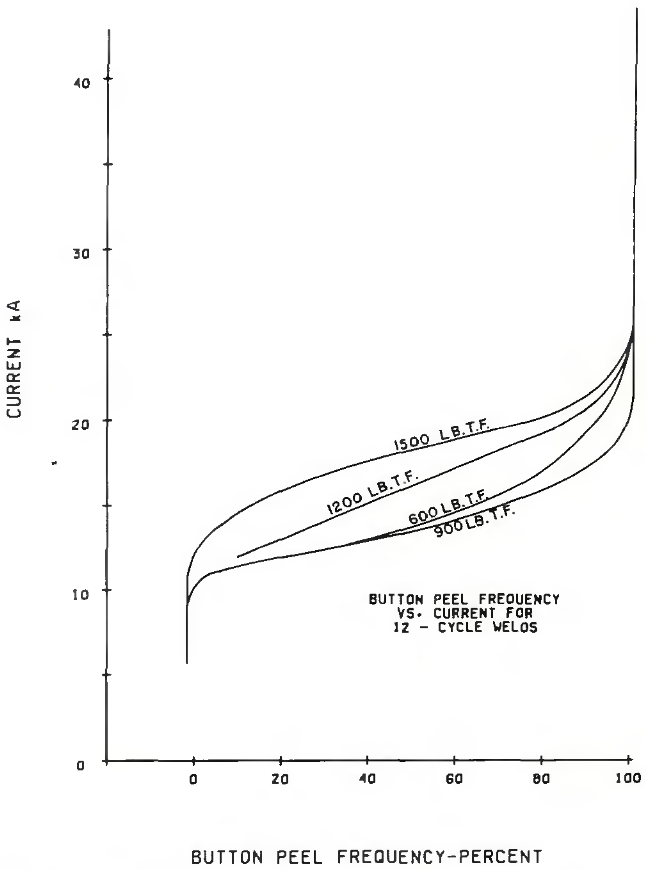

Fig. 12 — Percent peel vs. secondary current for 12 cycle welds

eral pattern that when enough current was applied to give good strength and button peel there were surface cracks. Series No. 97 at 12 cycles resulted in good welds, while series 96 and 98 which bracketed it, had 7% and 13% surface crack frequencies, respectively. The longer duration of weld current allowed the movable electrode to react and retard the formation of cracks.

Figure 5 shows the current versus tip force plot for three cycle welds. Compared to the one cycle welds, there was a considerably increased range of current and tip force where good welds resulted. At 900 lb (4005 N) tip force good welds resulted when the current was varied from 14.7 kA to 22 kA and at 1500 lb (6675 N) tip force from 23.3 kA to 33.2 kA.

At 1200 lb (5340 N) tip force the only series which resulted in good welds was the one which used 25.9 kA. The profile study data had some areas where it appeared to be inconsistent with the other results; one being the data for 1200 lb (5340 N) tip force. It is seen in Fig. 6 for five weld cycles that none of the series had good welds at 1200 lb (5340 N) tip force. The three series in the poor peel frequency area each had one weld which failed to peel a button, therefore, by the quality criteria used these were classified as poor weld series.

Figure 7 shows an increased range of current and tip force, which resulted in good welds at eight cycles current duration. Figure 8 for 12 cycle welds shows a very broad range of currents and tip forces resulted in good welds.

Figures 9 and 10 show the relationship of surface crack frequency to weld strengths as functions of weld duration and tip force. Figure 9 was plotted for 600 lb (2670 N) tip force and Fig. 10 for 1500 lb (6675 N) tip force. At 600 lb (2670 N) tip force it was difficult to make welds free of surface cracks which met the AWS-RMAS requirement. The 1, 3 and 5 cycle weld crack frequencies increased from nearly zero to virtually 100% as the weld strengths increased from 340 lb (1513 N) to 500 lb (2225 N). The 8 and 12 cycle welds had low surface crack frequencies up to 600 lb (2670 N) shear strength.

Figure 10 shows that at 1500 lb (6675 N) tip force and all cycles the welds remained free of surface cracks up past 500 lb (2225 N) shear strength. The 8 and 12 cycle welds approached 700 lb (3115 N) shear strength and still exhibited no surface cracking.

Figures 11 and 12 are plots of button peel frequency versus current for 3 and 12 cycle welds as a function of tip force. At currents greater than 24 kA the 12 cycle welds peeled 100% buttons. Above this same current the 3 cycle welds all peeled buttons except two series, Series 9 at 30.6 kA and 1200 lb (5340 N) tip force and Series 114 at 45.2 kA and 1500 lb (6675 N) tip force. Both of these sets of welds had high frequencies of expulsion and surface cracking which were indications that the welds were not sound.

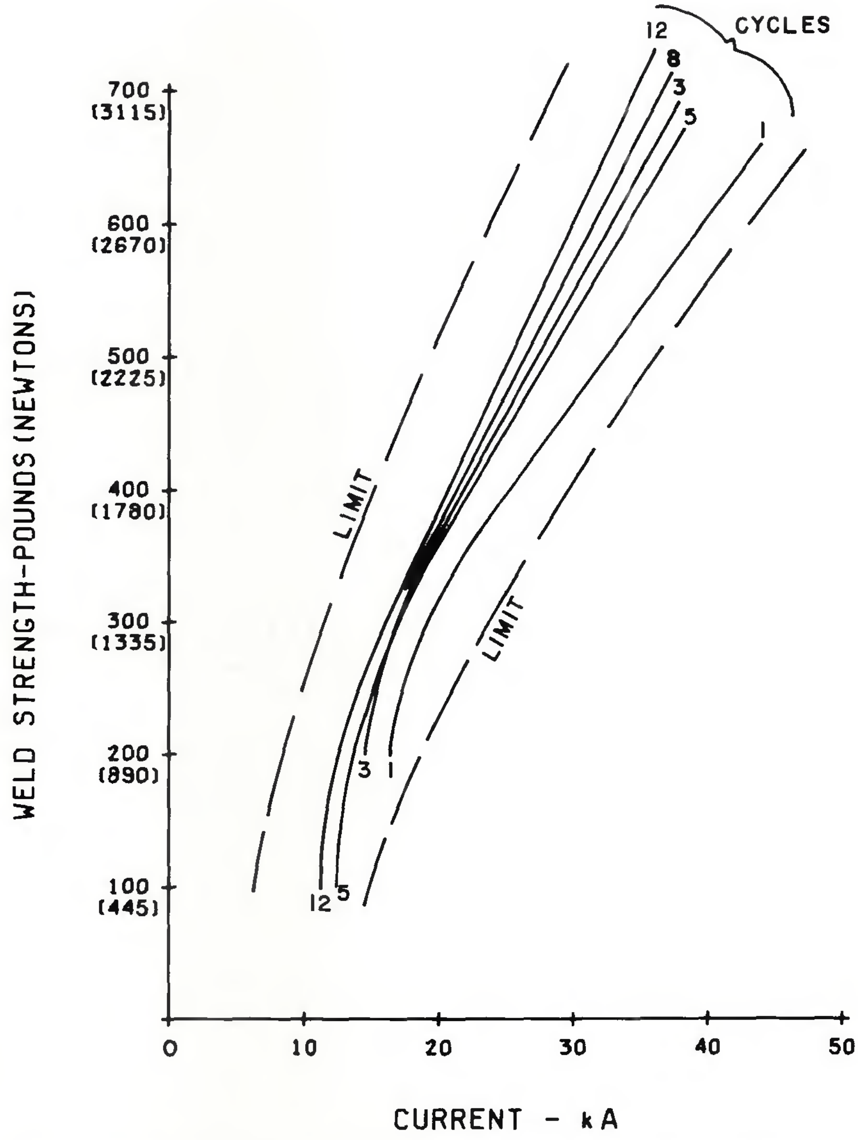

Fig. 13 — Weld shear strength vs. welding current for various current durations

Weld strength as a function of current is shown in Fig. 13. The limit lines show the vast range of weld strengths which resulted from a given current. If all the 135 average strengths were plotted on Fig. 13, they would be fairly evenly distributed in the area between the limits.

The data for the 3, 5, 8 and 12 cycle welds tended to fall at random between the limits regardless of the tip force. The data scatter was such that weld strengths could not be predicted with too much accuracy for a selected set of welding parameters. However, the general relationship of weld strength and current was nearly linear for the entire profile study.

The one cycle shear strengths fell to the right of the other data. On the average it took more current to make a weld of a given strength at one cycle than at 3, 5, 8 or 12 cycles. Between one and three cycles the weld nuggets were still enlarging, but by three cycles welds had essentially reached their final nugget size and shear strength.

Conclusions

During this program, which was designed to show the interrelationships and effects of the basic welding parameters, (i.e., current, weld duration and tip force) on the resistance spot welding of 2036-T4 aluminum, it became apparent that a significant amount of future work should be done in several areas to fully understand the process. These studies include surface oxide thickness variations on spot weldability, optimizing the welding parameters to achieve longer electrode tip life and the use of lubricants to stabilize the sheet surface and reduce tip contamination. The results of these studies will form the basis for future papers on the individual subjects. The data generated in this report form the foundation to conduct these other programs. However, the following conclusions may be drawn from work conducted on this program.

1. As tip force is increased, there is a larger tolerance in the variation of the other welding parameters, i.e., current and weld duration where good weld quality is obtained.
2. Longer weld current duration reduces the tendency to have cracks appearing in the sheet under the electrodes.
3. There is a near linear correlation between welding current and shear strength which is independent of the number of weld cycles and tip force used.
4. The results presented in this paper form a broad base to which the performance of other aluminum alloys and resistance welding equipment may be compared.

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WRC Bulletin No. 198
SEPT. 1974

"Secondary Stress Indices for Integral Structural Attachments to Straight Pipe"

by W. G. Dodge

"Stress Indices at Lug Supports on Piping Systems"

by E. C. Rodabaugh, W. D. Dodge and S. E. Moore

This report presents a simplified method for calculating the stresses induced in straight pipe by thrust and moment loadings applied to lugs and other integral attachments. Following the philosophy of the nuclear power piping portion of Section III of the ASME Boiler and Pressure Vessel Code, appropriate secondary stress indices are defined. A simple and conservative formula for computing the stress indices is developed using analytical results as a guide. A comparison is made between experimental stress indices and those obtained using the simplified analysis procedure developed here as well as the more complex analysis procedures of *Welding Research Council Bulletin 107* (WRC-107 method). The method is extended to attachments having a variety of cross sections.

Stress indices and the appropriate simplified design formulas are developed for analyzing integral lug attachments on straight pipe according to the philosophy of Section III of the ASME Boiler and Pressure Vessel Code for Class I Piping Systems. Indices are developed for the evaluation of primary stresses, primary-plus-secondary stresses, and peak stresses due to internal pressure in the pipe for radial thrust and transverse shear forces and torsional and bending moment loads acting on the lug; and for a thermal gradient between the pipe and the lug. The indices for thrust and bending moment loads are based on an extensive parameter study and are represented by simple formulas that may be used directly by designers and/or incorporated into codes and standards. From comparisons with other methods of analysis these formulas are considered to be more accurate and easier to use. Indices for the other loadings are based in part on strength-of-materials theory and information in the literature. Specific recommendations are made for incorporating the stress indices and design formulas into the ASME Code. As an example, a simple pipe support design is analyzed using the recommended formulas.

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