Variation in Aluminum Spot Welds

Spot welds deserve more faith than they have received but the fault is due more to what is not known than to intrinsic unreliability

BY R. A. CHIHOSKI

ABSTRACT. Aluminum spot welding has always been plagued by difficulty in meeting consistency specifications. The problems with equipment experienced early in this art have been solved competently. Then, surface conditions were rightly referenced as causes of inconsistency. This was done so convincingly that many cleaning lines were built next to welding units to make it easy to meet the common requirement to weld within 48 hours of cleaning. Some difficulty remains, evidenced a few years ago by the MIL Specification expansion of the allowed variation and the discouragement given to welding bare alloys like 2014 and 7075.

It was after a long troubling effort in 1968 to pass military type qualifications on some 2014 alloys that the accumulated evidence began to point toward a characteristic of the weld, and absolved suspected machine performance. While joint strengths were varying up to ± 30% the nugget diameters consistently came out within ± 5%. It turned out that there was a baseline strength attributable to the nugget and it was very consistent. But surrounding the nugget and varying for a variety of reasons was a diffusion bond. The phenomenon was especially significant on light gages, on newly cleaned material, and on bare alloys. When the standard distribution is calculated from the joint data a large probable spread was evidenced, supposedly representing a wide, flat distribution curve and unreliable results. In fact the *nugget* strength variation was quite narrow.

In any experience of variable tensile results the distinction between equipment malfunction and surface problems is easy to make. If nugget diameter is consistent, the heat formation weld parameters can be assumed consistent. If nuggets are not consistent, some parameter variation is the likely cause. But in the case of inconstant strength but constant nugget diameter a diffusion bond may be sought. Further evidence is easy to find:

1. The pressure ring around the nugget fracture has a dull satin appearance.
2. The stress rate in a tensile test may be jogged when the diffusion bond breaks separately and earlier than the nugget.
3. A histogram distributing the frequency of strengths of a number of spots may be bimodal (peaking at nugget strength and at nugget plus bond strength) or skewed, with the long taper to low strengths for newly cleaned material, to high strengths for older material.

Incidentally, when the diffusion bond effect is removed the same nugget diameters produced by different parameter routes have close to the same nominal strengths.

The remedies may be to discourage bonding by aging the material in air 20 hours before welding; changing the mechanical or chemical cleaning; or making a weld schedule or electrode radius change with this phenomenon in mind.

Any remedy will be more or less effective with different weld schedules, alloys, or thicknesses. But the underlying truth is that the welds are far more reliable than calculated strength distribution curves may indicate. The wide normal distribution curves and the sometimes high sometimes low welds frighten designers and earn a reputation of unreliability for aluminum spot welds. An unfortunate consequence is an unnecessary diminishing use of aluminum spot welding in structures.

Some recognition of the phenomenon by specification custodians may allow corrections in specifications and processes that will permit upward deviations acknowledging them as superfluous strengths that are not to be taken as signs of unreliable performance. Old and new engineering test data can be examined to know whether the stresses were exerted on the bond or the nugget, or a mix. The ability to encourage or discourage a bond giving results reliably on one level or the other may be exploited to pass consistency tests (static or fatigue) or to enhance the property of the joint. Controlling this effect may be used to some advantage in the resistance welding of other metals as well.

Just the recognition of the phenomenon may allow apparently incoherent data to be sorted into distinctive experiences. This paper deals with:

1. How the discovery was made.
2. The proof of its existence through tensile data.
3. The effect of time in air on strength.
4. The effect of changing cleaning procedures.
5. The effect of weld schedule changes.
6. The significance of the bond in design calculations.

Introduction

More than one company has been faced with an urgent need to prove its ability to make consistent spot welds and on occasions found itself unable to do so. The situation may have arisen with a new qualification prerequisite to production, or during a recertification required for some reason after a long, truly successful use of a given weld schedule. Sometimes the need arises when Quality Control has stopped the operation because of evidence of inconsistent output and surprise arises when the certifying technicians seem to be experiencing insurmountable difficulties. Sometimes engineers with a proposed design in hand ask for proof of the suitability of a spot weld but the weld technician cannot produce the trustworthy narrow distribution of strengths. Also, when a configuration has been used for years, the engineers could be shocked to hear of inconsistencies that cannot be diminished. Indeed the cruel irony often is that the harder the weld technicians try to produce a consistent string of welds, the more inconsistent it becomes. Usually the right combination of conditions is finally hit in a retest and the immediate problem, but not the uneasiness goes away.

A recent survey of aerospace resistance welding facilities revealed situations such as those, and found the

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following reactions. One company was about to return a newly delivered spot welding machine whose manufacturer could not qualify it. Two companies indicated a steady decline in the use of spot welds by engineers because of lack of confidence. Another large company gave up resistance welding entirely, turning over this joining operation to neighboring job shops and eliminating it from its own repertoire. Another company under close scrutiny of Quality Control was preparing to redesign some spot welded assemblies with expensive bolts and rivets just to eliminate the uncertainty. In some places, engineers are refusing to call out spot welds in the most obviously suitable locations.

It is true that the inconsistency that is so often the complaint voiced against resistance welding can stem from an interplay of several conditions. But, the many affecting variables when listed in defense of the operators only produces a mood of helplessness.

The authors' plant experienced its period of anguish when inconsistencies were found in spot welds of a certain assembly and a weld machine rehabilitation did not make them go completely away. The rework uncovered some mildly slow tubes, and a sometimes sticking pressure-dump-valve on the press type spot welding machine. The repair had a good but not complete effect. In the greater investigations, not even new schedules, the perfected machine, and the specially careful preparations would produce a strength scatter safely inside of the required specification margins. A relatively good qualification run of 100 tensile specimens would be followed by an extremely poor qualification run (wide scatter of strengths). Yet both were prepared according to the same schedule. The randomness of the quality seem to be unexplainable.

The military specification MIL-W-6858C was read over and over for insights into what was possible or permissible. Statements there that discourage or nearly prohibit the welding of non-clad aluminum alloys and alloys such as 7075 or 2014 suggested an actual inability of welds in these material combinations to meet that specification. An earlier revision permitted 90% of qualification specimens to fall within $\pm$ $12^1/_2$% of the average of the group instead of the narrower $\pm$ 10%. It removed the limit on the number of specimens in a test lot which could exceed 25% of the average. The allowed $\pm$ 30% variation of production parts and the permission to vary machine settings $\pm$ 10% suggested something that did not compliment the process or encourage precise thinking, although the joints were quite strong and economically applied. It was evident that aluminum welding problems were common and not just local.

The information coming out of retest after retest of our 2014-T6 0.080 to 0.050 in. thick combination was not even coherent. It seemed on one day a set of conditions would produce an average weld strength of 1700 lb in shear and on another day the same set would produce an average of 1200 lb. On other days, the specimens were high or low in random order producing a very wide distribution curve that appeared to justify complaining engineers' opinions that spot welding was a process that was unreliable and had no respectable controls. The mystery was compounded by the very high and low spot weld strengths produced from weld nuggets with equal diameters. Some frustration was produced in bystanders by the uncanny ability of the tensile machine operator to call out the low strength welds and the high strength welds while they were being stressed. One time, on another spot welding unit with other schedule and material combination (0.025 in. 2014), a qualification run that produced welds that ranged 200 lb from the average 470 lb—the worst qualification ever seen. Yet when the *same* pieces of material were rewelded after 5 days and much handling, no weld was farther than 30 lb from the average.

What is probably the largest influence on consistency will be discussed in the following text even acknowledging inconsistencies introduced by machine, material, and electrode variances that do also indeed affect spot weld strength. It must be appreciated that the measurable reaction to one of several variables has to be isolated and by isolation understood and thereby, perhaps, controlled. The phenomenon to be described now is an example of a factor that can with ease halve or double the strength of a spot weld. Just knowledge of how this can occur allows that inconsistency to be removed and the phenomenon to be exploited. The exposition and explanation will be simple and straightforward and, perhaps as a consequence seem too elementary to have ever been a mystery. But it must be remembered that before the rationale was exposed there was only an ensemble of apparently incoherent, inconsistent and contradictory experiences.

Table 1—The Change of Qualities of a Spot Weld as the Holding Interval Between Cleaning (by sanding) and Welding is Increased.

	I	II	III	IV	V	VI	VII
	Span between cleaning and welding, hr	Mode value of strength, lb[a]	Mode value of nugget diameter, in.[a]	Value of bond, lb[b]	Value of nugget, lb (II — IV)	Apparent ultimate stress of weld, kpsi (II ÷ N area)	Ultimate stress of nugget, kpsi (V ÷ N area)
a′	.035	1800	.261	700	1100	33.6	20.0
a	.035	1260	.251	700	560	25.4	11.3
b′	.290	1580	.250	700	880	32.1	17.9
b	.290	1380	.250	700	680	55.3	13.8
c′	.700	1695	.256	675	1020	32.9	15.6
d	1.5	1400	.252	630	770	28.1	15.4
e	3.0	1360	.253	570	790	27.1	15.7
f	5.5	1210	.252	490	720	24.3	14.4
g	16.5	1410	.256	360	1050	27.4	20.4
h	31.5	1170	.245	320	850	24.8	18.0
i	72.	1140	.245	300	840	24.2	17.8
j	150.	1150	.250	295	855	23.2	17.4
k	264.	1230	.255	290	940	24.0	18.4
l	1000.	1100	.252	260	840	22.1	16.8

[a] Pertains to Fig. 1.
[b] Pertains to Fig. 8.

Method of Experiment

The following experiment was run sometime after the rationale was uncovered. It was run in order to provide a systematic proof and calibration of the discovered effect in this combination of materials with these weld conditions.

Twenty spot welds were made per set of specimens. In the *a* set each specimen was welded within 2 min of cleaning by sanding of the two surfaces of 0.080 in. thick $^3/_4 \times 5$ inch strip of 2014-T6 and the two surfaces of a 0.050 in. thick 2014-T6 strip. Thus the span between cleaning and aging was 0.035 hr for each specimen in the *a* set. Each specimen in the *b* set was welded 17 min (0.29 hr) after cleaning. Every set of the twelve sets was welded after a prescribed time as denoted in Table 1. The longest cleaning to weld delay (C-W Span) was given to the *l* specimens.

These were welded 1000 hr after being cleaned.

Chemical cleaning—flash etch and chromic-acid deoxidation—is the most common method for cleaning aluminum for welding. But in this plant the build plan which installs a 0.050 in. baffle in a 10 ft dome that has spent several weeks being fusion welded would not allow the common 48 hr limit between chemical cleaning and resistance welding to be met. So cleaning of these pieces and the specimens is accomplished by disc sanding with a 180 grit paper shortly before spot welding. Surface resistance checks even indicated the average results could be more consistent and lower than batches received from the cleaning operation. Wire brushing used one time earlier produced wide results because of reactions to bristle position, and surface speed, pressure, and stroking style.

Sixteen specimens out of each set were pulled and the values recorded. The diameter of the face of the fractured nugget was measured with an optical comparator and recorded. The remaining four specimens had the nugget drilled out and reamed out to the average nugget diameter for the set; and then they were tensile tested.

Surface resistance checks were made on the typical specimens at increasing spans from cleaning. Plots most indicative of trends were made and are discussed in the following section. The weld schedule employed in production and test is given in Table 2.

Discussion

The Data

The character of the specimen distribution for each clean to weld delay (C-W Span) is presented without interpretation in the Fig. 1 plots. In the *a* plot, the strength and diameter of each specimen welded in two minutes is marked by a data point. A histogram showing how frequently certain strengths occur has been drawn on the right hand margin. In *a* it shows that the majority of specimens ranged between 1650 and 1950 lb but a few dropped to 1500 and 1300 lb. The nugget diameters of the *a* welds had a range of 0.250 to 0.263 in. By scanning the plots from *a* through *l*, it can be observed that the strengths drop and the dispersion of strength values narrows. It can be seen that the nugget diameters decline slightly and cluster more tightly around a single value.

The peak of each distribution, the curve mode, represents the nominal specimen better than the average. So, a typical *a* specimen should have coordinates of 1800 lb by 0.261 in. in diameter.

The coordinate value of the two modes specifies the center of the cluster of data points. In the *c* set, the center has moved to 1690 lb by 0.256 in. in diameter. If these centers are plotted on the same ordinates as Fig. 1 the shift of strength and diameter with increasing C-W span can be traced. The locus of centers drops in strength (Fig. 2) with little decrease in diameters to *f*. Then the strength and diameters wander down and up a 24 kpsi line. This indicates that the cast strength of the nugget is constant at 24 kpsi and nugget area changes are accompanied by proportional weld strength changes. The *b* and *g* data are somewhat anomalous in an otherwise consistent trend of results so they have been discounted in several of the curve smoothing processes.

The *a* set center seems to have an ultimate stress of 33.6 kpsi (1800 lb ÷ nugget area) *c* of 32.9 kpsi, *i* of 24.2 kpsi, and *k* of 24.1 kpsi. This no doubt produced a puzzle in the past because the nugget appears to grow very weak for no known reason. If the strength were a constant 24 kpsi then all strength-diameter combinations would fall on that constant stress line. Is the *a* nugget extraordinarily strong or the *k* nugget extraordinarily weak? And what makes them differ?

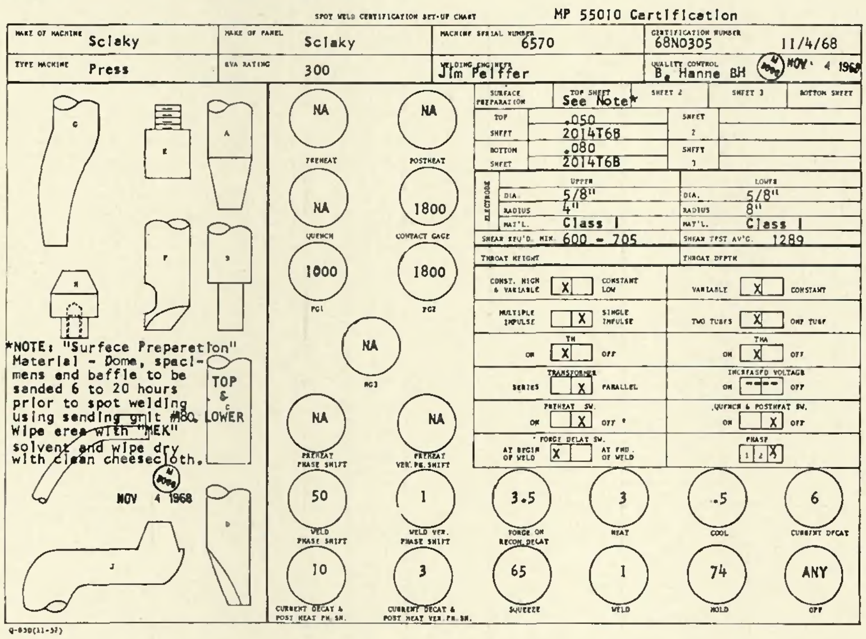
The shift of strengths with increasing C-W span can be more easily seen if the frequency profiles from each set in Fig. 1 are placed on their own time station as in the strength vs time plots of Fig. 3 where the histograms of Fig. 1 were correctly located on the time ordinate (divided logarithmically) and strength distribution curves were approximated over them. This presentation makes the three remarkable features of the time transition visible: wide scatter of strengths for specimen welded within 10 hr of cleaning, an extraordinarily tight distribution of strengths after 30 hr, and a tendency for the early sets to have strengths clustered at two levels (giving bi-modal distribution). The information presented here after an isometric style is seen more cleanly in Fig. 4 in which topographic lines denote the bounds of scatter. The actual experimental data points are also included here on their own time line. This curve was the goal of the experiment and is the most valuable display of information in this report. The usefulness of the Strength vs. Cleaning-to-Welding-Time curve (S vs C-W Span) will be demonstrated in later discussion.

The strangeness of its pattern is emphasized by the Nugget Diameter vs C-W Span curve (Fig. 5) which roughly parallels the strength curve between 30 and 1000 hr. But the wide uncertainty of strengths in the young specimens is not paralleled by uncertain diameters. Too many of the *a* and *b* and *c* welds are much stronger than they should be when their diameters are only 0.260 in. The solution that was given during the difficult qualification period turned the anomalous experiences into pieces of a logical pattern. Since then that solution seems to have been justified.

The Theory

In aluminum spot welds the nugget is surrounded by a halo or polished

Table 2—Nominal Weld Setting Schedule


SPOT WELD CERTIFICATION SET-UP CHART
MP 55010 Certification
MAKE OF MACHINE Sciaky
MAKE OF PANEL Sciaky
MACHINE SERIAL NUMBER 6570
CERTIFICATION NUMBER 68N0305 11/4/68
TYPE MACHINE Press
KVA RATING 300
WELDING ENGINEER Jim Peiffer
QUALITY CONTROL B. Hanne BH NOV 4 1968
SURFACE PREPARATION: TOP SHEET See Note* | SHEET 2 | SHEET 3 | BOTTOM SHEET
TOP SHEET .050 2014T6B
BOTTOM SHEET .080 2014T6B
SHEET 2
SHEET 3
ELECTRODE: UPPER — DIA. 5/8"; RADIUS 4"; MAT'L. Class I
LOWER — DIA. 5/8"; RADIUS 8"; MAT'L. Class I
SHEAR REQ'D. MIN. 600 - 705
SHEAR TEST AV'G. 1289
THROAT HEIGHT
THROAT DEPTH
CONST. HIGH & VARIABLE [X] [ ] CONSTANT LOW
VARIABLE [X] [ ] CONSTANT
MULTIPLE IMPULSE [ ] [X] SINGLE IMPULSE
TWO TUBES [X] [ ] ONE TUBE
TH: ON [X] [ ] OFF
THA: ON [X] [ ] OFF
TRANSFORMER: SERIES [ ] [X] PARALLEL
INCREASED VOLTAGE: ON [----] OFF
PREHEAT SW.: ON [ ] [X] OFF *
QUENCH & POSTHEAT SW.: ON [ ] [X] OFF
* FORCE DELAY SW.: AT BEGIN OF WELD [X] [ ] AT END OF WELD
PHASE 1 2 X
PREHEAT NA
POSTHEAT NA
QUENCH NA
CONTACT GAGE 1800
FG1 1000
FG2 1800
RG3 NA
PREHEAT PHASE SHIFT NA
PREHEAT VER. PH. SHIFT NA
WELD PHASE SHIFT 50
WELD VER. PHASE SHIFT 1
FORCE ON RECON. DECAY 3.5
HEAT 3
COOL .5
CURRENT DECAY 6
CURRENT DECAY & POST HEAT PH. SH. 10
CURRENT DECAY & POST HEAT VER. PH. SH. 3
SQUEEZE 65
WELD 1
HOLD 74
OFF ANY
*NOTE: "Surface Preparation" Material - Dome, specimens and baffle to be sanded 6 to 20 hours prior to spot welding using sanding grit #180. Wipe area with "MEK" solvent and wipe dry with clean cheesecloth.
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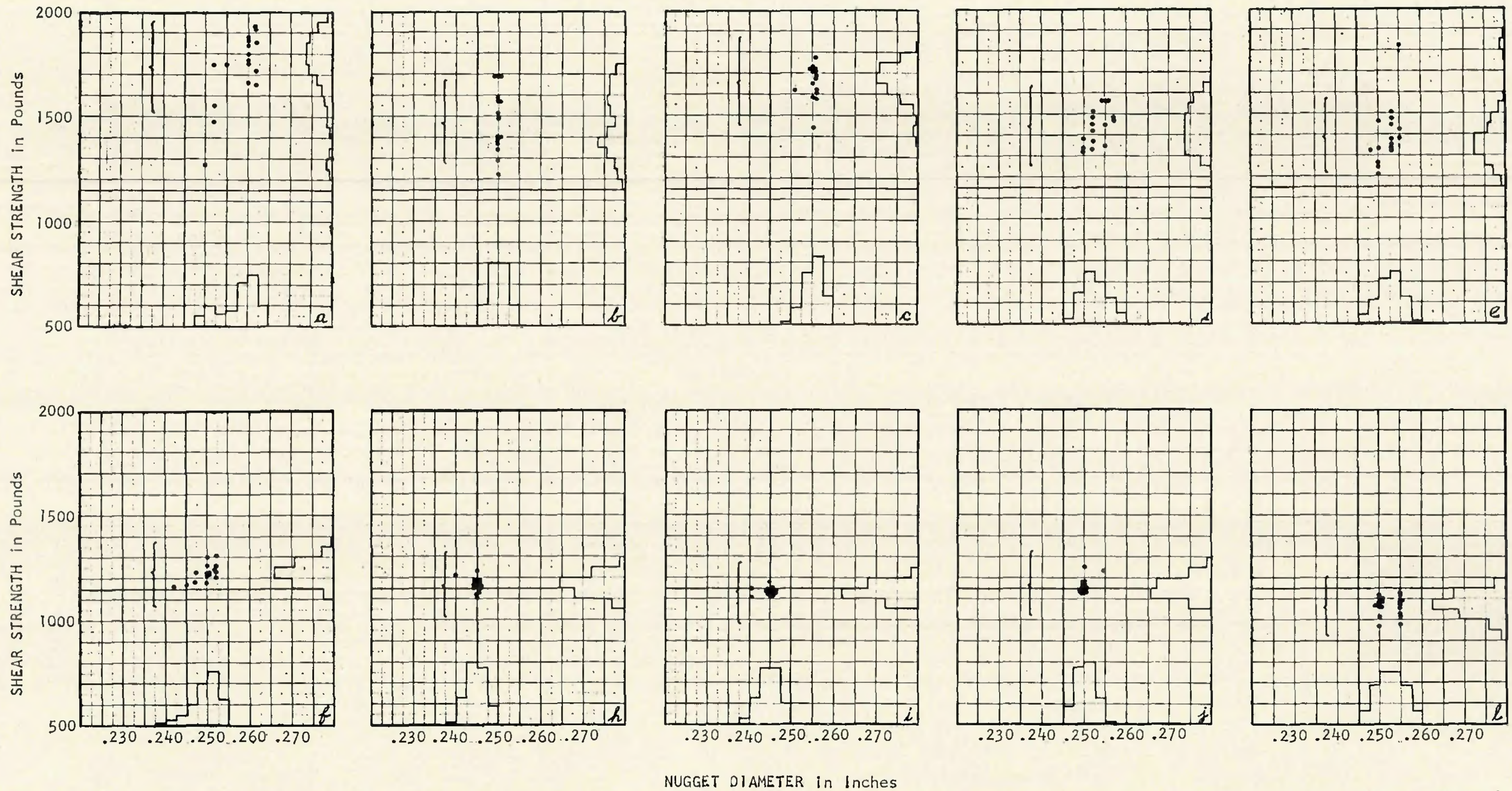

Fig. 1—Each plot represents a set of 16 spot welds that has been welded at a specific time interval between cleaning and welding. With increasing interval the weld strength drops but the scatter of results narrows remarkably. Nugget diameter drops mildly

surface identified in different places as a corona, a heat or pressure ring. When strength outside the nugget was postulated it was noticed that there was a barely detectable difference between the ring on a "strong" specimen and a "weak" one. The ring on the strong one had a slightly more satin or silky lustre than the weak one which had the typical polish of a planishing mark. Figure 6 shows two welds and their pressure rings. It was considered then that the difference between the family of welds of 1700 lb strength and the family of 1200 lb which may be found in one test lot might be a 500 lb diffusion bond outside of the nugget that only *sometimes* was there to reinforce the nugget.

The tensile machine operator came to be able to sense a difference between the weak and strong specimens. If a specimen, while being pulled, "clinked" between 400 and 1000 lb and the machine needle fell back momentarily then it could be called out as one with a lower value. This, when consciously considered, was attributed to the diffusion bond parting independently leaving the nugget to bear the load alone. If a 500 lb bond held, then it and the 1200 lb nugget would part together at 1700 lb load.

The testing lab would often report a good qualification run except for a number of seriously low specimens. The weld technicians would use cleaner, fresher material, for their next welds and drive the average toward 1700 lb yet never eliminate the few low ones (1200 lb) that would fail the qualification.

Now, if the diffusion bond is encouraged by the absence of a thick oxide film on the unusually fresh aluminum surface, but is prevented by the thicker oxide barrier on older surfaces, then the irony was that it was the low specimens that had the nominal values and the high specimens although more numerous were spurious. Instead of answering the question "Why did the low specimens occur?" the more appropriate question should have been "Why did the high specimens occur?" when qualifications were run on materials which by direction had been held more than 16 hr since cleaning (although under protest because of the "unnecessary" lost time) 98% of the specimens came within $\pm 12^1/_2\%$.

All clues supported the answer—the action of a bond. But since they only provided indirect proofs the argument could not be concluded. In this experiment the last four specimens in each 20 piece welded set were treated differently. The nugget was drilled out and reamed out to the diameter of the average nugget of its own set (see Fig. 7). The direct proof of a bond would lie in whether the specimen had strength after its nugget was removed. Some time before the problem was engaged anyone might have expected the specimen pieces to fall apart when the hole was made. Certainly none would expect that 700 lb might be required to pull such a couple apart. In fact the *a* specimens without the nugget did have shear strengths between 630 and 775 lb. This bond carries 40% of the load of a 1900 lb test.

But if the bond served intermittently the weld specimens would be intermittently high or low. One of the early clues was a bi-modal distribution of results in several Qualification tests. This distribution was seen in a histogram of the specimens but not in the calculated normal distribution curve supplied by a mathematician which exaggerated the strength spread. According to it, three standard deviations reached from 400 to 2600 lb.

The strengths of the bonds are shown in Fig. 8. (The roman numerals refer to the column numbers in Table I which lists the average points used in the following figures; Fig. 8 in-

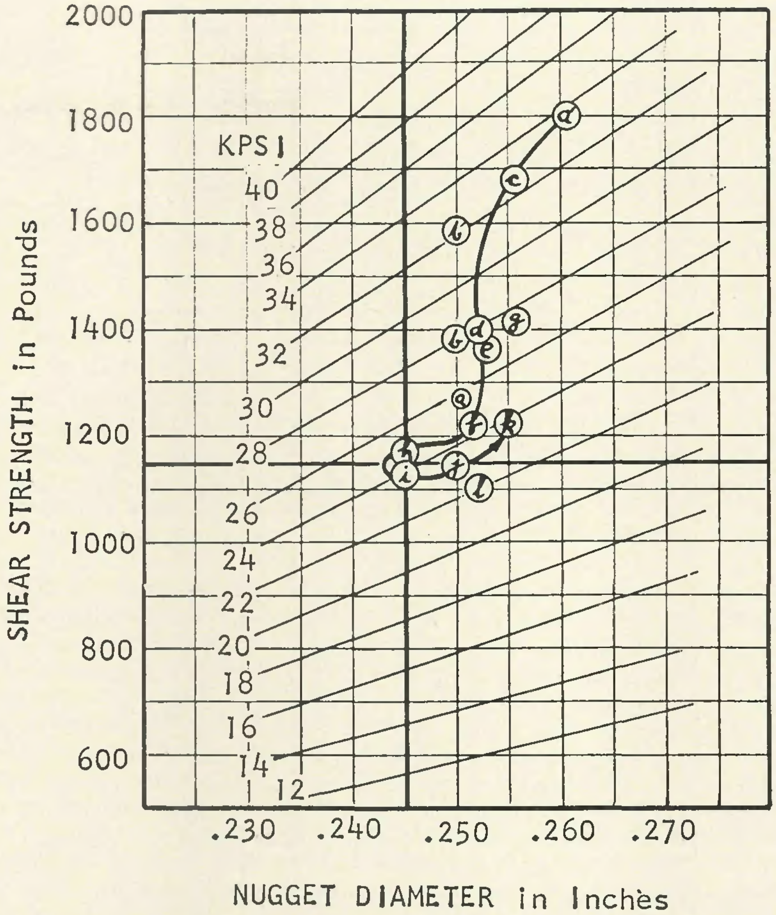

Fig. 2—From the typical a weld (where the weld strength ÷ nugget area gives an ultimate stress for the nugget of 33.6 kpsi) the locus of the most typical weld moves down in strength without a proportionate decrease in nugget diameter for larger intervals up to 6 hr (f). For welds made between 16 hr and 264 hr (g to k) diameter changes accompany proportional strength changes and the nugget cross section appears to have a constant 24 kpsi ultimate strength

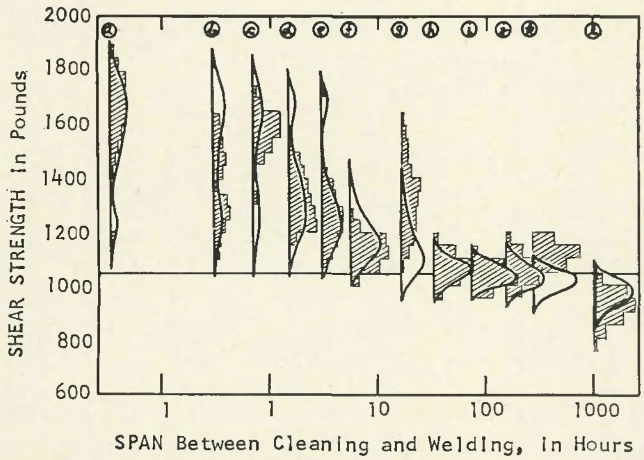

Fig. 3—The characteristic distribution of strengths of each time set is approximated from the histogram distributions transferred from Fig. 1. Most of the systematic changes as a consequence of greater holding time become visible

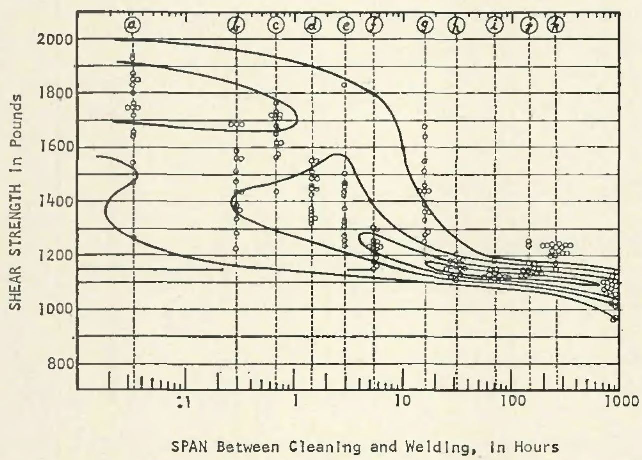

Fig. 4—The distribution of strengths is wide in the early specimens. It is apparent that the earliest specimens will give an unusually high strength that disappears in time. In the spans where it is disappearing (b thru f) the strength tends to occur by either high mode or low mode which emerges a little later. When the ambiguity has ended, the scatter around the low mode becomes very small and remains narrow until the specimen surfaces have become very old. Then variety begins to increase again

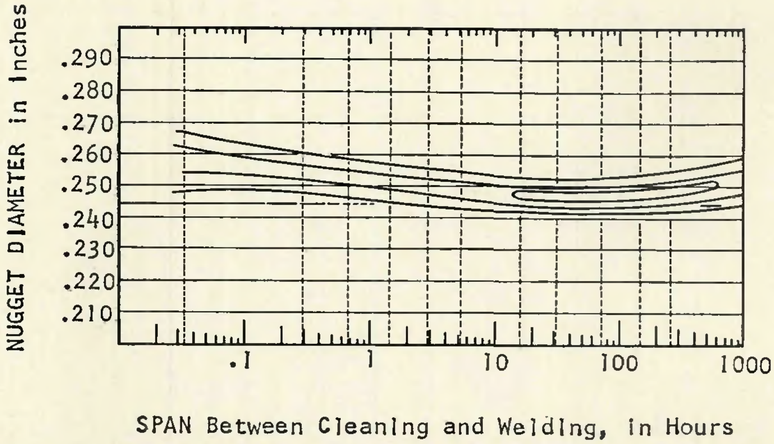

Fig. 5—The nugget diameters remain relatively stable and narrowly distributed reflecting consistent maintenance of weld parameters. The ambiguity in strengths of the early specimens is not repeated by ambiguous nugget diameters.

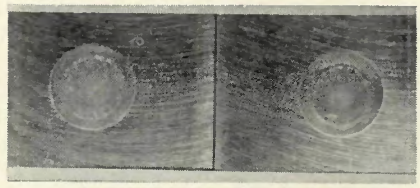

Fig. 6—A weld out of the a set that pulled at 1750 lb is placed next to one out of the k set that pulled 1240 lb. Both nugget diameters are 0.255 in. and in all other respects they are indistinguishable

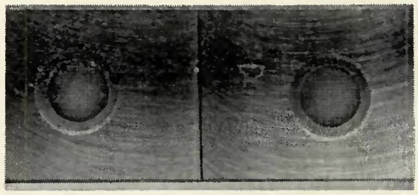

Fig. 7—An a set and k set specimen had their nuggets drilled and reamed out before the tensile test. The pressure ring remaining is visible here. It took 635 and 260 lb respectively to pull these pieces from their mate

cludes actual specimen data points.) As expected, the bond weakens as the welded surface becomes older. The wide scatter of results ought to be attributed to the experimental techniques rather than the fact. Where the scatter of weld strength is only ± 50 lb in Fig. 4 a ± 200 lb spread in one component (the bond, Fig. 8) should not be expected. It is no subtle effect which has been extracted and isolated. The outside-of-the-nugget strength might now be considered a fact. The explanation of the bond may be considered a reasonable theory.

In Fig. 9 the weld strengths were drawn. It may be seen that the strength difference between the upper mode (II′) and the lower mode (II) disappears after 20 hr. The *nugget* strength (V′) was also drawn. It was found by subtracting the *bond* strength (IV) from the upper mode (II′) *weld* strength. For example, the *c weld* may pull at 1725 lb but because the *bond* was found to carry 675 lb, the *nugget* alone must have had a strength of 1050 lb. The lower mode, curve II, looks like it is really the true weld strength when the perishable diffusion bond disappears. There are reasons for postulating that the bond strength (i.e., 675 for *c*) consists of a large unreliable diffusion bond (330 for *c*) and a consistent nearly constant "perimetal" bond (345 for *c*). Metallographically one might guess such a perimetal ring is 0.015 in. wide laying just outside the edge of the nugget itself (see Fig. 10).

It is interesting to find that the nominal 300 lb difference between the nugget and the lower mode weld gives a perimetal ring 0.015 in. wide when its bond strength is assumed to be 20 kpsi.

The irrational behavior of the apparent ultimate stress—the *weld* strength (II′) ÷ nugget area, (VI)—is clear in Fig. 11. What was once found to be the ultimate stress of the cast nugget could hardly decline 25% (33 to 25 kpsi) without some detectable change in diameter, penetration, metallography, or recorded expansion. When the ultimate stress of the *nugget* is calculated (col. VII) and drawn, the strength of the nugget runs between 20 and 17 kpsi. Eliminating the bond assistance from the gross strength of the weld exposed the relatively constant ultimate stress nugget that was wanted. Those historic experiments which did avoid making diffusion bonds in their specimens would divide the weld strengths (the lower mode (II) results) by nugget area and

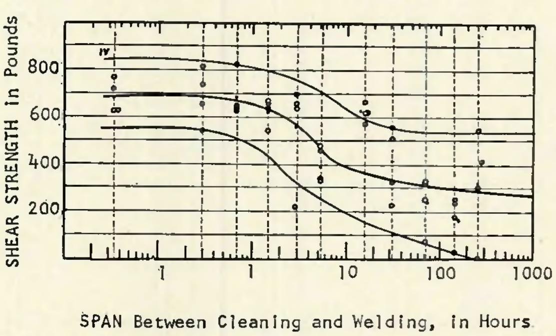

Fig. 8—The strength of the bond, that is the strength of the joint with the nugget drilled out is plotted here (IV) for all the holding time sets. The initial decline is attributed to the disappearance of the diffusion bond. The bond strength that remains at 260 lb is speculatively attributed to a coalescence just outside the perimeter of the nugget itself. Some old specimens may not have this at all

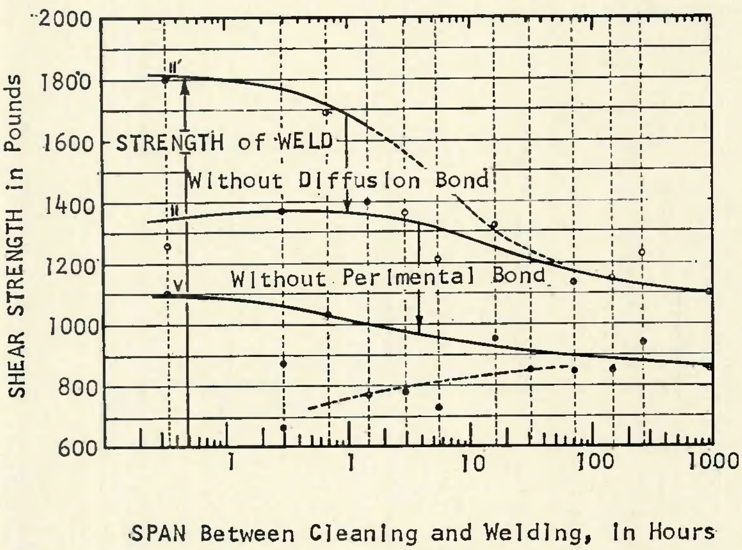

Fig. 9—When the maximum weld strength mode (II′) from Fig. 4 is plotted and the bond strength (IV) is removed by subtraction the strength of the nugget alone (V) is indicated. The strength of the weld without the diffusion bond (II) is still above the nugget indicating a perimetal bond consistently surrounding the nugget

come up with rational ultimate stresses but more on the values of the VI curve (25 to 23 kpsi). Such a value now seems may be a sum of the strength of the nugget and the perimetal bond.

Looking back to Fig. 8 the curve seems to describe a bond strength at two levels. There is an accelerating decline from *a* to *f* which stops near *g*. In our argument this corresponds to the disappearance of the diffusion bond. The strength of the remainder, the perimetal bond, declines but levels out around 300 lb. In more time or by different finishes the perimetal bond width may disappear or shrink to insignificance as the non-metallic film on the surfaces of the work becomes more impervious to current and atom transfer. Some of the oldest specimens had bond values of zero. The perimetal bond may really be a partially fused interface. It is essentially constant and has probably been undetected, being, by most practical criteria, an integral part of the weld. By contrast, the theme of this report, the diffusion bond, must be formed over a wide area in the solid state by time, temperature and pressure across a thin barrier. It may vary in density from weld to weld and especially between electrode face changes and also across and around the pressure ring, and it slowly fades away from welds on older surfaces. It would seem to be an effect to be avoided.

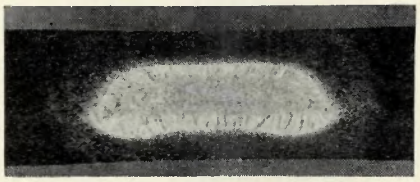

Fig. 10—A typical spot weld in dissimilar thickness material with different radius electrodes. The perimeter of the nugget may be ringed by a narrow welded bond that is not part of the cast mass

The Business of Welding

While this suggests another look at design attitudes and specifications, the manufacturing engineers and the men around the machines will be able to profit from this view and optimize what they may accomplish under existing specifications. Some of the possible pitfalls can be easily and consciously avoided.

The MIL Specification (MIL W 6858C), which is a good standard for measuring a process, requires 100 tensile specimens for a qualification of new or rebuilt equipment. The strength of 90% of these must lie within ± $12^1/_2$% of the average of the lot. None of the remainder can lie 25% below the average. The brackets laid into the plots of Figure 1 indicate the span of ± $12^1/_2$% inside of which 14 of the 16 specimens should fall in order to pass. One can see that the odds of passing are not good for a lot of specimens cleaned 2 min before welding (*a*), or 20 min (*b*), 42 min (*c*), $1^1/_2$ hr (*d*), or 3 hr (*e*). By contrast, specimen lots cleaned anywhere between 30 and 200 hr will produce extraordinary consistency. Since most procedures constrain testing and welding to within 48 hr of cleaning some time near that would be satisfactory.

Figure 12 shows the scatter of strengths produced on 100 specimens of 0.025 to 0.025 in. thick 2014 T6 aluminum sanded and welded within 1–3 hr. The results were disreputable. 55 specimens fell outside of ± $12^1/_2$%. Suspecting the bond, the very same material (after the welds were cut off) was welded with the same weld schedule and the same surfaces touching. By the second welding time, the surfaces were 100 hr old. In spite of the long holding time and the much handling only five specimens fell outside of ± 12½%. The strength was lower but above minimum required.

The scatter of the *b*, or *c* or *d* lot by itself is not extremely bad. What more often happens is that the specimens do not have the same age. If 50 couples of material were cleaned early Monday morning and 50 couples were cleaned in the afternoon and the first group welded with the second later in the afternoon the results would look like Fig. 13. 65% of the specimens would fall outside of the ± $12^1/_2$%. Now, if the 100 couples cleaned that way on Monday were for some reason welded Friday afternoon, which would give them an age of 101 and 90 hr respectively instead of .7 and 6 hr, the results could like like Fig. 13, where no specimens fall outside. In other words, *do* use material which has been cleaned at the same time.

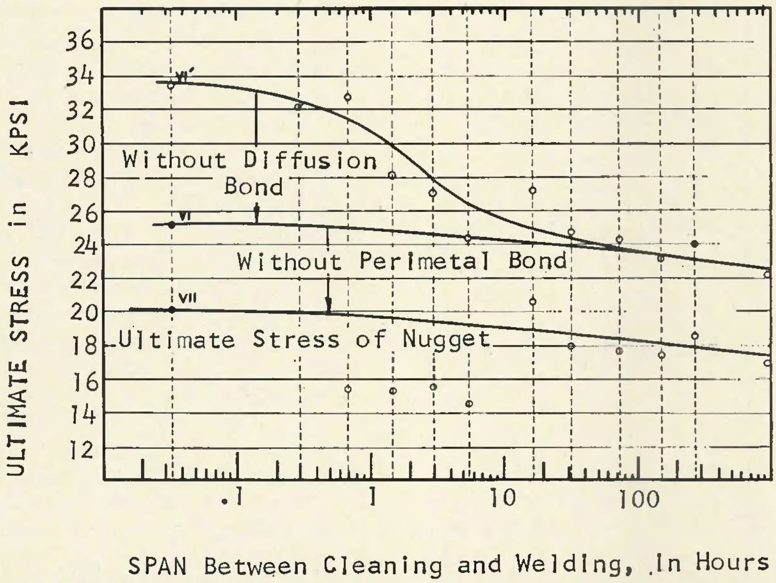

Fig. 11—Ultimate stress, determined by ultimate shear strength ÷ nugget area, appears to diminish severely on older specimens. When the calculations are repeated on nugget strength (i.e. weld strength less bond strength) the cast metal appears more constant in its sectional ultimate stress

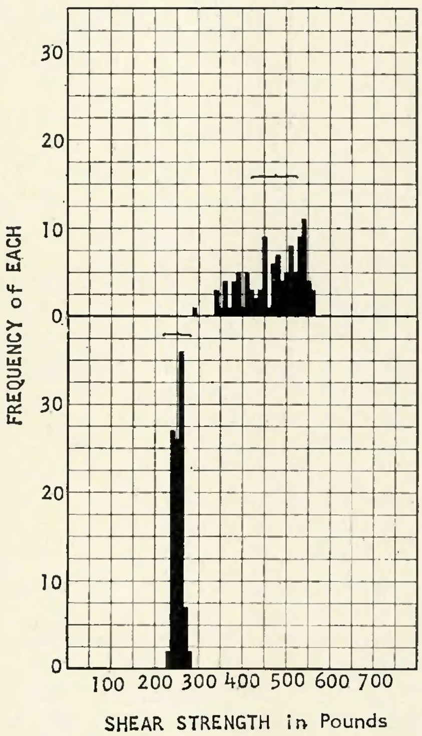

Fig. 12—One hundred specimens of 0.025 in. thick 2014 welded within three hours of sanding produced results from 280 to 520 lb. The same pieces rewelded 100 hr later scattered from 230 to 280 lb

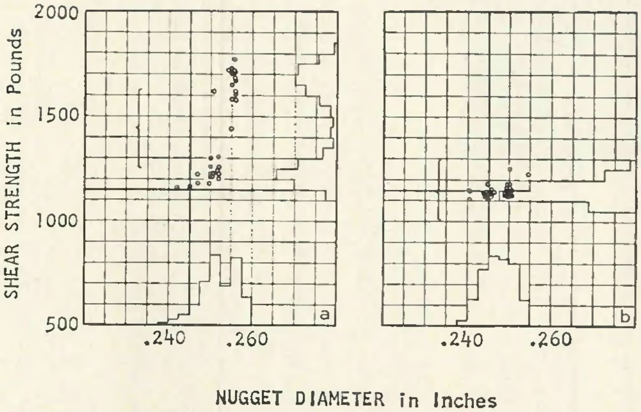

Fig. 13—Welding the subject material cleaned .6 and 7 hr before produces two families of results, and a wide scatter. Waiting 95 hr after the second lot produces essentially one family and a very narrow scatter

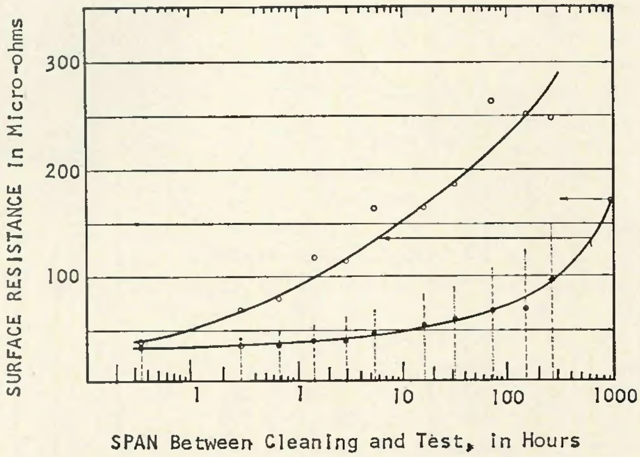

Fig. 14—The resistance rise of 2014 surfaces in air in time are compared for chemically cleaned (upper) and sanded specimens. The resistance reached in 700 hr by the sanded material is reached in 7 hr by the chemically prepared surfaces. This suggests that chemically cleaned aluminum acquires impediments to resistance welding far sooner than sanding, and that this experience may be avoided

But if this cannot or has not been accomplished then the longer the assortment is kept the smaller the time differential, and so the surface differential, between pieces becomes.

The curves and margins drawn from the experiment in this report apply only to the identified material, weld schedule, and cleaning technique. For example, only for the specified weld conditions can it be said that "old" material, 30 to 200 hr from cleaning, will give the least scatter, such as ± 50 lb, as a result of surface condition. The general character of the curve, however, should be repeated but changed in degree and proportion for any set of weld conditions.

The important dimensions of a Strength vs C-W Span curve can be seen in Fig. 4 with the particular values out of Fig. 4.

1. The strength of the high mode (1800 lb).
2. The strength of the low mode (1400 lb).
3. The latest time a high mode specimen will occur (10 hr).
4. The first time a low mode specimen will occur (2 min).
5. The span time in which the specimen might have either a high or low mode value (2 min to 10 hr).
6. The time when scatter becomes satisfactory (30 hr).
7. The time when scatter is minimized (70 to 200 hr).
8. The low mode decline of strength (60 lb between 20 and 200 hr).
9. The time when scatter begins to increase again (250 hr).
10. The time when it has become excessive (1200 hr).

Most of these characteristic dimensions can be measured on the Strength vs C-W Span curve made on other alloys, other schedules and cleaning techniques. The curve will tell if there is a surface and time combination that gives seriously ambiguous strength results. It will tell if there is an optimum time for welding, and where and how long it lasts. It will tell if and where there is a critical over-age, that is when scatter expands excessively.

An experiment is being run here now on material chemically cleaned (by a nitric-chromic acid deoxidizer). The results are expected to reflect a thicker, faster growing impeding film on the parts. The higher resistance of a chemically cleaned couple is shown next to the sanded couple in Fig. 14. The effect on welds should be seen as a lower high mode (1), that disappear sooner (3); a higher low mode (2), that starts abundantly and sooner (4); a steeper strength decline (8); and an earlier scatter increase (9); and an earlier scatter to excess (10).

The clearly increasing scatter in Fig. 4 after 700 hr can be attributed to the sum of two effects. The scatter of diameters which is apparent (see Fig. 1, *l*) and the now sometimes non-appearance of the perimetal bond which is suggested by the oldest specimens in Fig. 8. The perimetal bond and the nugget diameter could become variable on account of high surface resistance thick films found on old material or some chemically cleaned surfaces. The current-conducting aluminum interface during the weld could have an abrupt and discreet boundary compared to a tapering current density level on lower impedance films. The thick film might be breaking down in steps during current flow.

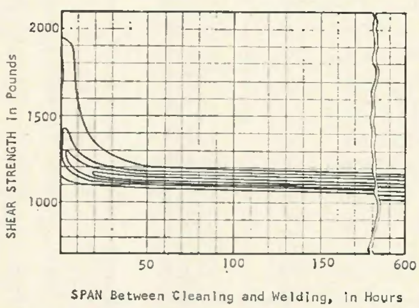

Fig. 15—In order to correct the impression created by the proportions of the logarithmic time scale, Fig. 4 curves were replotted on this uniform time scale. It can be seen how, in the scope of 180 hr, the diffusion bond ambiguity exists for relatively brief time, but in the span in which resistance welding often is required to be finished

Figure 15 is Fig 4 redrawn on a uniform time scale in order to correct some of the illusions created by a logarithmic time scale. It reduces the apparent extent of the ambiguous period and shows the extraordinary duration of the safe period (consistent strength) that is *possible* from aluminum alloy spot welds.

Now the usefulness of the Strength vs C-W curve for making things happen optimally may be clear. For an investment of 240 spot weld specimens the time may be found when the most consistent welds should be made. If one S vs C-W curve does not expose a useful character when perhaps another curve run after a different cleaning process will contain the low scatter in a reasonable time span (which is usually a manufacturer's most desired objective); at last now the ambiguous random appearing results that are due to holding time can be eliminated.

Just as a different cleaning method may produce a modified curve a change in the weld schedule may do the same. The shape of Fig. 4 curve would probably be more changed by weld pressure or electrode radius than any other parameter change. A heat change should just displace the curve upward or downward. By an experiment that redraws the curve after an innovation, certain effects may be observed and desired effects found. Thus the set of weld conditions that produces the minimum scatter or the set that gives the highest shelf life tolerance may be noticed and applied to production.

The high mode may be found in some cases to give high strength reliably and the set of conditions that will guarantee it can be exploited. Steel was found to do this. The high mode was found so strong and reliable in 21•6•9 CRES that it was possible to join meteoroid detector panels with spot welds that were stressed only on the diffusion bond. The technique allowed a lower weld heat, which was desired, on a thin/thick combination (0.002/0.016/0.002 in.), and the production of over 100,000 welds was completed without a defect. And, every test (static and fatigue) that was made on specimens gave a strength that was within ± 5% of the average.* Any process change can be evaluated according to whether the new S vs C-W Span curve is preferred to a prior one. In many cases these presentations can steer a process directly toward a desired end. If a small decrease in electrode radius gave more consistency but lower static and fatigue life the manufacturer may elect a further increase or decrease depending on what he needs.

Time as an instrument has been neglected. A late weld can be more useful than an early weld. A weld at a particular time may produce what was rare but desired results. The absence of time from experimental control or notes has often meant only anomalous results were recorded, because the instrument worked, but randomly and out of sight.

In the subject case, only because of the thin material, the bare alloy, and the sanding does this phenomenon and its extraordinary reaction to time stand out so prodigiously that it is visible above the background of the other usual variables that always play into the data.

Data from other schedule-material combinations were reexamined. This effect was detectable. But because it was mixed with several other contributors to scatter it was not discovered when the data was first recorded. Nevertheless, as a component of scatter it is very large under some conditions. Its elimination will be, more or less, a definite improvement. The subject experiment was carefully run so as to change only the clean-to-weld span. Other sources of variation were fortunately successfully precluded allowing the distinction attributable to time to stand out clearly without a massive number of data points. Even then some curve smoothing required the discounting of some aberrant data which may have come from a machine, electrode, or cleaning change.

With regard to other influences, it was found that small differences, such as between the power banks of the machine, produced their largest effect in the time sets that were most indecisive (*b, c, d, e, f, g;* i.e. 17 min to 16 hr) where the specimens may be inclined to go to the upper mode or the lower mode by the slightest influence. Therefore, always avoid magnifying the influence of machine, operator, or cleaning inconsistencies by working outside of ambiguous areas. If a person had to diminish the effects of inconsistency of a machine he would have a combination that was cleaned

*Chihoski, R. A., "Resistance Welding Thin/Thick Materials," *Assembly Engineering,* April 1970.

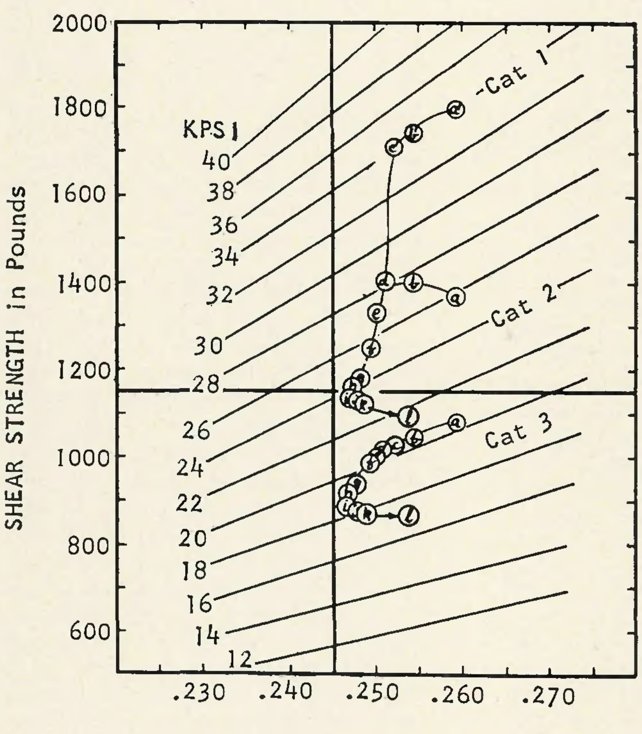

Fig. 16—There is defined in this report three categories of spot weld. This plot of the locus of typical specimens of each set helps distinguish the categories and the ambiguous states between them. The shifts across the constant stress lines represent shifts from one category to the other

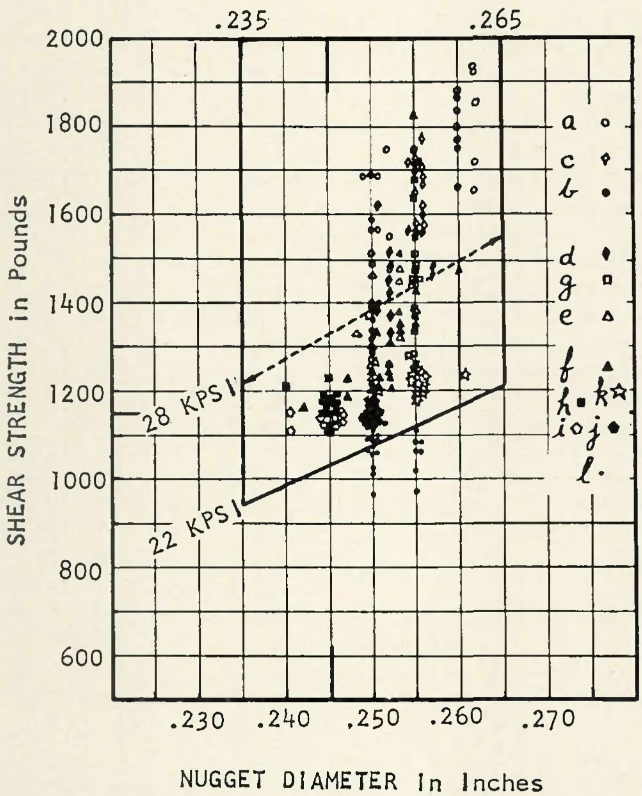

Fig. 17—To ignore, practically, the superfluous strengths of the bonds, direction can be given that no more than 1% of the subject spot welds of any size test lot can fall outside the heavy boundaries. The nugget diameters and the lower limit become in effect the only constraints. Here are all the data points produced in this experiment. Only the I specimens would bring a test failure. In practice most specimens would fall inside the parallelogram

on Friday welded on Monday, not Friday or Saturday as he might be inclined.

Highly variable strengths in a test or trouble shooting expedition are misleading when the nugget or the machine are not variable. Specimens in the *g* set may scatter over 450 lb but all with a 0.255 in. diameter nugget. This leads to a most important rule: Machine and process consistency is more fairly measured by nugget diameter than by strength. Now if a report of inconsistency is turned in, an investigation of typical nugget diameters should be made first. If the nugget diameters are found variable and proportional to strength, the problem may be usually laid to the machine (or extremely high resistance surfaces). If the diameters are relatively constant, the problem is less serious and attriibutable to material preparation and clean-to-weld timing.

Anticipating results from more study it appears that chemical cleaning will be shown to be the cause in the industry of more uncertainty about weld results than it has been a remedy. There are data which show:

1. Five different proprietary deoxidizers will produce five different surface resistances (between 10 and 94 μohms).

2. The resistances will generally rise the longer the material is kept in the deoxidizer, but differently for each and not proportionately with respect to time (in the first 10 min, between 4 and 24 μohms/min in solution).

3. The holding span in air produces somewhat different resistance rise rates for material from each solution. Some are very high and rise steeply. Others are low and rise little—which seems desirable—(in one day the resistance can rise from 10 to between 40 and 100 μohms depending on the deoxidizer).

In other words, different cleaners will produce different results, or a cleaner used differently (i.e. time in solution or rinses, or temperatures) will produce different results, and (as reported here) different C-W holding spans will produce different results. Except for the extraordinary diffusion bond on young surfaces more consistency comes out of the sanded material. Apparently most of the deoxidizers create their own peculiar film or conversion layer (that gives a surface resistance higher than sanding) which also increases faster in air than sanding (see Fig. 14). The results are similar to pushing the curve in Fig. 4 to the left off the field and spreading the scatter (9) sooner from a wider band than seen in Fig. 4. Sanding is peculiar because it does produce the purest alloy surface and it has linear asperites that are mashed under electrode force, adding diffusion, keeping resistance lower, and creating a uniform moderate impedance to current flow. The high resistance value that took the sanded parts 700 hr to reach was reached by the chemically cleaned parts in 7 hr. If the welding reactions are analogous to surface resistance then the late scatter in the subject experiment (Fig. 4, 1000 hr) will begin to appear on material cleaned by this solution after 20 hr in air. Thus it seems that cleaning solutions in this class (the majority of cleaning solutions) will produce material which looks like late Fig. 4 material—that is, it will carry a heavy non-conducting film that causes that ambiguous period when the perimetal bond no longer occurs consistently.

It overlaps a period of inconsistent breakdown of the heavy film by current which becomes only worse in time. The last is characterized by inconsistent nugget diameters, non-round spots, fast nugget expansions, and spits.

The texture also plays a part in the reaction to spot welding. The stated effects of thick non-conducting films are reduced or delayed by toothy or grainy surfaces, and exaggerated by bright polished surfaces. Either type surface may arrive from the sheet mill or be produced by one of the cleaning selections. Two points are made:

1. The same chemical could produce different curves (reactions) from the different textures.

2. The rougher texture can reduce variety from older or thicker surface films.

It seems that the solutions put together for cleaning, deoxidizing, desmutting, or mildly preservative reasons have served those purposes well. Welders have run some tests and chosen the best of the lot. But which of these or which of any possible chemicals can produce the most consistent results over a longer span is a question that still may be appropriately asked and profitably answered. The strategy for solving these problems was discussed earlier. More inconsistency can be traced to the material finish and holding time than most manufacturers have ever realized.

Designs and Specifications:

The engineer and the customer are looking for an explicit definition of properties, and assurances that the properties, with reasonable tolerances, will be delivered. The purpose of a specification is to guarantee these by means of certain tests—stating, what a machine or company must accomplish to be considered qualified for a range of work; what a detailed process must give to be certified able to produce certain results; and what standards must be maintained during production.

The allowed latitude in resistance welding may seem too generous: $\pm 12^1/_2\%$ of the average from a test, $\pm$ 30% in production. Consternation may be appropriate when the margins cannot be easily achieved. Loss of confidence may be appropriate when no explanation can be given for excessive variety. These are the experiences that lead to the avoiding of resistance welding of aluminum. Now, the manufacturing engineer can do something as shown toward narrowing the output range by consciously choosing the conditions that put results in one slot, that is around one mode avoiding conditions prone to ambiguities.

There is another option which, after the understanding of the reported phenomenon, may be acceptable. A new definition of performance may simplify the application of spot welds. The subject combination will be used as an illustration. There has been defined three categories, or plateaus, upon which spot weld results may be found:

1. The nugget surrounded by the perimetal bond and that by the diffusion bond.

2. The nugget surrounded by the perimetal bond.

3. The nugget surrounded by no coalescence.

In our example, specimen holding-time-in-air moved categories from one to the other. Generally, a thickening surface film should do the same. Between 1 and 2 there is a phase of ambiguity, the variety maye be narrow around each mode but the results fall sometimes under one mode sometimes the other. (2 is very stable and long lasting on the subject weld.) Between 2 and 3 is another phase of ambiguity (perimetal bond or none). The last uncertain phase (past 3) gives true scatter as nugget diameters become inconsistent. Figure 16 (derived from smooth curves from Fig. 4 and 5) illustrates the levels. The *a*, *b*, or *c* sets give an apparent strength of 36 kpsi for the category 1 welds. Category 2 is well populated with *g*, *h*, *i*, *j*, *k* (20 thru 200 hr) specimens at the apparent 24 kpsi. By taking the bond away as was done in the experiment the nuggets are shown to really have a strength, so far as tested, between 20 and 18 kpsi (the lower curve). The upper curve was expected to descend finally to the 16 kpsi level and go no further although undergoing wide variation of diameters on that level.

Now if a 16 kpsi nugget is sufficient, and it seems to be because the design manuals give a minimum Class A weld strength of 700 lb, then all the strength above 16 psi may be considered accidental and superfluous. Consistency should be rated on how frequently this lower limit is penetrated. Thus within limits the nugget diameter and strength may vary freely along the 16 kpsi line in Fig. 16. Strengths may lie high on the plot, but not below the set stress value. No handicap would be associated with higher strength nuggets provided the diameters fell within the limits that reflect process consistency. A quantitative value for consistency may be taken from a distribution of *nugget diameters* in a lot. But more relevant for the designer or stress engineer the reliability will be based on the lower half of the distribution from the fixed norm.

This seems like an awkward or complicated procedure (in practice the format can be made simple, see Recommendation). Its institution can be justified from two points of view. First, because the results from averaging and determining the standard deviation misrepresents the probable scatter as ranging from very high to very low; when in fact there is a very firm floor under the strength values.* Elimination of the poor and varied results falsely implied by the traditional procedure may repair the lack of confidence which affects impressions and decisions. The second reason may be the high cost which is being paid for apparent reliability. Efforts are continually exerted—an additional step or special stock control—to keep the strength up and narrowly distributed or down and narrowly distributed. The effort could be eliminated if the superfluous high strength increments were ignored.

The task of giving proof of the validity and arranging the special calculation should not be a deterrent since the dollars saved by improvement in the operations will probably overwhelm the trouble of initiation. Figure 4 shows that in truth a sanded part can be welded anytime between 2 min and 700 hr later without changing *nugget* strength by more than 85 lb (770 to 855 lb, vis à vis nugget diameters of 0.247 to 0.259 in.). The kind of liberty allowed by appreciation of that does eliminate overtime, shelf life control (dating and handling), recleaning exercises, and waits for the right time to weld.

*The results are not represented by the Gaussian distribution curve always employed, but in truth by a curve skewed upward and essentially truncated at low *nugget* strengths on the low side.

By recognizing and permitting without penalty category 1 and 2 specimens to populate the lot with category 3 a larger dollar saving can be realized. And further, with conviction that nugget strength (now identifiable separately) has remarkable small variety and is *less* likely to pierce the lower design limit than previously calculations showed. The weld technician can produce a schedule more aptly satisfying the relevant requirement avoiding compromises on weld pressure or electrode radiii made to suppress the effects of a mode he was not aware of. With a little more freedom perhaps he can steer away from a crack or spit incidence. Currently, engineers use the conservative design manual values for spots. When they want a stronger assembly they usually draw more spots, if they can. With this grip on the problem they may be made reliably in category 2, and the technician can show whether they can be delivered. As in the previously referenced meteoroid detector panels, high performance welds of category-one can be specified and delivered under favorable conditions.

The MIL specification fortunately allows procedures alternate to those contained in it to be used on approval. Too often this clause is not permitted to be employed. As a result a move which may be taken to improve the joint or the economy of the operation is prohibited. For example penetration from 20 to 80% on a roughly elliptical nugget is expected by everybody concerned with an aluminum certification. No one will support the individual who proposes a dog-bone cross section although he may show it to have some superior and no inferior qualities. Part of the reason is the mystery which surrounds much of what happens in resistance welding and a fear of leaving the worn path. The irony is presently that understanding, rather than new kinds of equipment, will make the bigger economic and engineering successes.

The problem of static shear strength, as has been seen, is not one of low strength but one of reliability. The specifications require for the subject weld at least 700 lb. This is the value allowed by strength design manuals. A consistent 750–850 lb nugget is eminently more satisfying to the designer than a lot of 25 that runs from 900 to 1800. The large spread predicts mathematically that some percentage of welds will be below and far below the 700 pounds, which is not true in fact.

But a good many designers are concerned more with the fatigue on cyclic properties of the weld than the static. Since this is a complicating factor the lack of confidence given to static expectation is multiplied for cyclic expectation. The variability of a given batch should be greater for fatigue results than for static results. It is proposed that the same phenomenon described as operating without control on these static results is one of the major operatives on fatigue variability. This is not to say that the highest static strength equates to the highest fatigue strength. The subject thesis says there are three kinds of spot welds with three kinds of outer boundary. Whereas the whole coalesced area works for shear strength it is the character of the weld boundary itself that is most influential on fatigue results.

Without speculating on which should be superior in fatigue, it is apparent each will perform at a different level and, of course, a mix of specimens will give a mix of results. It is recommended that the distinction be pursued and some optimization of fatigue life research be conducted after the manner described for static optimization in the previous section. It is clear already that one kind of boundary will have to be selected and produced for a certain specific fatigue life effect. It is further recommended that any research be conducted without attention to external or internal process or specification constraints, for the moment, so that the results may be ranked just by the qualities sought.

For example, once a weld schedule was found for a difficult CRES foil to sheet to foil combination that produced the highest and most consistent diameter, strength and fatigue properties but the nugget always had an ellipsoidal pore right in the center of the core. The normally applicable specifications rejected this joint. But adjusting parameters to remove the pore produced less consistent results. Since the foil stressed the perimeter of the nugget, it was not hard to make this particular weld configuration an acceptable standard. When the *desired* results are outstanding then deviations from the traditional constraints should be boldly solicited and judiciously allowed. But a demonstrated understanding of the underlying reasons for certain effects, although not necessary, is the best security to have when turning into a new path.

Conclusions

1. There can be strength in a spot weld that lies outside of the nugget proper.

2. Such a strength reinforcement, which can amount to 40% of the weld strength, is most prominent on thin

bare aluminum alloy that has been sanded for cleaning.

3. Its contribution becomes more uncertain between 1 and 30 hr after cleaning; after which it completely disappears.

4. It must be a solid-state bond because it appears for a distance beyond the weld nugget. It occurs on freshly prepared surfaces with a low electrical resistance.

5. It appears that a spot weld nugget may be bonded by: a perimetal bond, and that by a diffusion bond; a perimetal bond; or no further coalescence.

6. Aluminum welds shift from the first to the third categories with holding time after cleaning (or a thickening high resistance interface) and this can be clearly seen in a Weld Strength vs Clean-to-Weld Time Span Curve. Conditions which are not designed to produce welds of specifically one category may produce welds randomly around one or the other categories. In the time plot, the periods between 1 and 2, and 2 and 3 are called the ambiguous periods.

7. That period of indecision produces widely scattered or bi-modal strength results. Small inconsistencies in other weld conditions magnify the weld strength variability of welds made during such a period.

8. The wide scatter of results in and between test lots is often due to a mixture of welds from several categories.

9. Reliability of the machine or the process is more clearly distinguished by measurements of the nugget diameter than by weld strength since diameter which reflects process parameters can be constant while strength varies greatly.

10. If stress calculations and designs were based on nugget strength the superfluous strength of the bonds that created a false scatter could be ignored. This would make it easier to appreciate and exploit the fundamental consistency of the cast weld.

11. Fatigue properties should be even more sensitive than static shear strength to the kind of boundary around the weld. The product (and the understanding) would benefit more by the identification, test, and production of a specific selected boundary condition.

12. Spot welds deserve more faith than they have received but the fault is due more to what is not known than to "intrinsic unreliability."

Recommendations

Having provided a wide knowledge of the various characteristics of the subject weld made by the subject materials and weld conditions it may be said that the weld should be treated by process and specification as follows. The nugget diameter should not vary $\pm$ 0.015 in. from 0.250 (at 22 kpsi ultimate stress this represents a strength tolerance of 1082 $\pm$ 125 lb or $\pm$ 11.5%). Since 22 kpsi is a good and reliable plateau, the strength should not drop below this.

Therefore, it is recommended that after certification per current practice that:

1. Not more than 1% of any sample size made as pre-production, in-production or post-production fall outside of the solid bounds indicated by Fig. 17.

2. That all time requirements laid on the interval between the sanding of part or specimens and welding be removed.

3. In case of question the subject materials shall not exceed 100 μohms in surface resistance.

Most specimens will fall within the parallelogram in Fig 17. The savings derived by adapting this recommendation may amount to 50% of the cost of this assembly operation.