ABSTRACT. It was once proposed that the lagging temperature rise (in the areas on the sides of a fast moving aluminum weld puddle) has the effect of applying a transverse compression on the post-puddle weld bead. Volume-change calculations supported this conclusion. But it was a considerable departure from the accepted and apparently obvious view of immediate post-puddle tension caused by the clear decrease in temperature of the centerline after the puddle.

In order to test this prediction a method was devised for seeing the volume change on the surface of panels heated by a moving welding arc. A 2014 T6 panel, scribed with parallel lines, was photographed normal to its plane before welding after it was in its fixture, to create a photographic negative of reference lines. Then, the weld arc was sent traversing the panel, melting the one free edge.

The peculiar volume expansions created by a moving heat source changed the shape of the panel, seen by the spreading and turning of the lines. As the "point-heat-source" (arc) crossed the axis of the camera lens, a second photograph was taken to capture the in opera shape of the panel and lines. The test lines change in ojiera), the welding speed, was too subtle to be plainly seen or appreciated. The first (reference) negative was laid over the second (test) negative at an angle and the combination enlarged and printed. The print displayed a pattern of Moiré fringes, locus lines where the test lines intersected the reference lines.

Photographic studies of aluminum during welding indicate that the volume-increase peak lies over and behind the puddle, a condition which reveals a compression that is rationally manipulable.

BY R. A. CHIHOSKI

Photographic studies of aluminum during welding indicate that the volume-increase peak lies over and behind the puddle, a condition which reveals a compression that is rationally manipulable by measuring the span between intersections. By many measurements the course of the test lines could be calculated and reconstructed on a scale that made the peculiar expansion effect of the point source obvious.

Three Moiré prints were made for three edge welds, one each at 6, 13 and 20 ipm (152, 330 and 508 mm/min). In these the expansions were presumed to grow without restraint into the free direction. In a second series, three Moiré prints were similarly made for three butt welds. In these, expansion is constrained in the test panel by its partner.

From the two series, six reconstructions were drawn. The test-to-reference intersecting angle was changed and six more Moiré prints were made from the same negatives. The test lines were reconstructed again. When they produced the same six interesting reconstructions, the results of the first series were verified. On the edge panels the expansion was manifest. The expansion peaked 0.207 in. (5.3 mm) after the arc center at 6 ipm (152 mm/min). It peaked at 0.680 in. (17.3 mm) after at 13 ipm (330 mm/min); and peaked at 0.744 in. (19 mm) after at 20 ipm (508 mm/min). The last two are far enough after to place the expansion peak after the puddle solidus.

When a change such as an expansion cell was seen in an edge weld specimen but not in its corresponding butt weld specimen, it was supposed that the area in the butt was experiencing a primary compressive stress. Thus, it appears that a compression node does follow the puddle in most cases, following further after with higher welding speeds. Other comparisons of edge and butt surfaces (seen in opera) indicate that a substantial amount of longitudinal expansion by the puddle is resolved transversely into upset, a puddle volume increase, and more expansion force. The potential tensile reactions before and after this compression node make the stress pattern more interesting and its wise exploitation more important.

With this pattern in mind it becomes possible to rationally select and test the weld conditions that may optimize the experiences of the weld metal after the puddle.

Introduction

The stress on the metal immediately after a weld puddle has not been a subject of much argument. The assumption that it experiences a transverse tension is instinctively and logically agreeable.

This premise is used in laboratory tests for the weldability of alloys where varying degrees of tension are exerted on metal specimens raised to selected high temperatures. The purpose of these tests is to indicate the relative weldability of different alloys by their ability to withstand that tension. Another approach to weldability is to make welds, and then

Paper presented during a session sponsored by the Aluminum Alloys Committee of the Welding Research Council during the AWS 60th Annual Meeting held in Detroit, Michigan, during April 2-6, 1979.

R. A. CHIHOSKI is Head of Welding Research in Advanced Manufacturing Technology, Martin Marietta Aerospace, Denver, Colorado.
make judgements.

Weldability should be defined as the ability to fuse an alloy without creating numerous defects, most notably cracks. An optimum set of weld conditions is the choice of all conditions, like edge preparation, filler metal volume, preheat, welding speed, and current that produces the least number of defects in a given long length of welding. The set of conditions that create one or two specimens of satisfactory welds for certification is not to be taken as the profitable "best set."

There is something disturbing about reactions to changes in weld conditions. The notion of a uniform decay of temperature and a coherent change in tension after the puddle implies that graduated and mild changes in results should follow from graduated changes in weld parameters. This often is not evidently the case. Reactions are meant here to describe changes in the detect rate.

Several years ago it was suggested and demonstrated by calculated volume increases that the most impressive aluminum just after the weld puddle may experience a range of stresses varying from the accepted tension to an extraordinary compression depending on conditions. If the proposition is true, it has to have a profound effect on the selection of weld conditions and the interpretation of weld problems, not to mention a revision of the standard axioms on post-puddle metallurgical and mechanical experiences. The acceptability of such a disquieting proposal depends, it seems, either on more evidence or another method that arrives at the same conclusion.

The work described in this paper has two purposes:

1. To devise a method for observing and measuring the volume changes around the weld puddle.
2. To observe and evaluate the volume and stress consequences of a parameter change such as weld speed.

It has been assumed here that if the nature of post-puddle volume and stress changes is demonstrated for one aluminum alloy, it will more likely than not apply to every aluminum alloy, although with coherent shifts in magnitude and location.

**Method**

The intent of this work is not to theorize but to observe the displacement of solid metal around a weld puddle. The technique selected for this end uses the Moiré fringe effect. To recall the Moiré fringe effect the following is provided.

The easiest Moiré pattern to describe is the one formed by a system of parallel lines of uniform spacing (call the spacing R) laid over another like it at a small angle (call the angle A). The intersections of the two systems of lines form a visible pattern. In this example, lines drawn down through those intersections would be parallel, straight and separated by equal distances (measured along one of the lines, call that spacing M). M can be found from $R = M \sin A$ by measuring M and A.

This idea is valuable because at small angles, M is a large multiple of R and a measurement of M will give an extremely accurate value for the R. The effect can be to provide a magnified exhibit of the movement or distortion of either system of lines over a large field at an instant of time.

The Moiré effect was exploited to find the pattern of expansion in a panel being welded. By laying a photograph of ruled reference lines over a photograph of a ruled test panel being welded the local distortions of test panel lines show up as changes in the M spacings.

A typical panel was 0.100 in. thick, 4 × 24 in. (254 × 102 × 610 mm) of 2014-T6 aluminum alloy black anodized and scribed to give parallel ruled lines 0.020 in. (0.508 mm) apart.

In each test a photograph was made of the panel after it was positioned.
The weld arc was then started and a second photograph was taken as the arc passed a prescribed point, capturing the in-welding shape of the panel. This created two negatives: the pre-weld and the in-weld situation. The pre-weld negative was laid over the in-weld negative at an angle that gave a Moiré amplification of 13 times. The negative set was pressed between glass plates in a holder, enlarged 2.8 times and printed. This print gave the ability to see the test panel’s in-weld line spacings multiplied 37 times.

Figure 1 shows a copy of the “Moiré” print for an edge pass made at 13 ipm (330 mm/min).

Since one objective was to detect the difference in weld stresses caused by weld parameter changes, it was part of the testing to measure the effects of different speeds and to search for the differences between them. The travels of 6, 13 and 20 ipm (152, 330, 508 mm/min) were chosen for this. Edge welds were most important. An edge weld has the arc and electrode traveling along the panel edge with the electrode axis directed down into the plane of the panel—Fig. 2A.

Because they are not restricted at the weld line, volume changes caused by a moving heat source would cause an edge line to move up and down with respect to its original position without opposition—that is, the weld fusion line moves as it might if it did not have a mate pushing and pulling oppositely at every point across the weld centerline as it does during a real weld. The real weld cannot graphically reveal the forces at work, but in the edge weld the rise of an in-weld test line over the normal line would signify intrusion into a theoretical partner or a force trying to push the two pieces apart. With the same logic a retreat to below the original line position would represent tension and a mechanical drawing-together of the sides. To a large degree the action of the edge demonstrates elastic change—that is, what moved away because of the passing heat returns eventually to the position it held before the pass.

It should be kept in mind that the volume profile is a traveling wave. Although its form is constant with respect to the electrode, the whole system moves from one end of the specimen to the other. This is quite analogous to a bow-beam-stern wave that keeps the same form with respect
to the boat creating it as the boat crosses a calm bay. Such a form has been called quasi-stationary. In an apt analogy, the wave changes to a revised and new form if the boat speed is changed or if the boat loading is changed.

Figure 2A represents the test apparatus arrangement for the edge weld, which is really no weld but only a 0.1 in. (2.54 mm) meltdown. The panel was clamped to a tempered fiberboard block along its lower edge. The GTA torch was positioned pointing down through the plane of the panel. The electrode was a $\frac{1}{8}$ in. (3.2 mm) diameter $2\%$ thoriated tungsten ground to a 30 deg cone with a 0.045 in. (1.1 mm) diameter flattened tip. At the travels of 6, 13 and 20 ipm, the current was 23, 35 and 52 amperes (A) respectively. A metal mask was placed over the arc position to eclipse arc light from the camera lens. The picture was taken as the electrode axis crossed the camera lens axis.

For a later evaluation and comparison to the edge weld, the wave peculiar to a real butt weld was photographically captured; again at each of the three speeds. These were horizontal welds—see Fig. 2B. The mating plate edges were tacked at both ends before the weld pass. Their surface was, as before, normal to the camera lens axis. The in-weld picture was taken when the electrode axis became coaxial with the camera axis. This strategy puts any parallax error away from the area of greatest importance. The same welding equipment was used to weld the 6, 13 and 20 ipm specimen but at 55, 70 and 100 A, respectively.

Six weld experiments were conducted: three edge welds (E’s) and three butt welds (B’s). Each panel, as before, had its own original negative laid at an angle onto its own in-weld negative so as to magnify the in-weld change with least error. Six Moiré prints were produced. They all represent a relation of reference lines (cold originals) to test lines (in-weld) called orientation 1. This has the reference lines ascending from the test lines in the direction of arc travel.

A change in the Moiré spacing M will come not only from a change in the distance between lines but from a change in the crossing angle; more exactly the sine of the crossing angle. In fact, in terms of M’s span, the effect
of small changes of already sharp angles can be many times greater than small changes in the distance between the lines. It turns out that, when the Moiré distance M grows, it is revealing ambiguously either an increase in space between lines or a decrease in the angle between intersecting lines. Likewise when M decreases, is it from decreased line spacing or increased angle? The method developed to resolve this ambiguity is described in this paper.

Moiré intersections were generated when a mat of parallel reference lines (RL) were laid over the test lines (TL) at an angle. The angle formed between the parallel reference lines and the parallel basic test lines (before being turned by the heat) is a constant dimension of the layup and will be called A.

Figure 3A shows the results of laying on an RL system that cuts against the TL rise. The Moiré fringes, the vertical pattern of intersections, can be discerned. They are seen as uniformly spaced on the left side of the field indicating two crossed systems of parallel lines. The fringes are closer at the top right where the lines cross at larger angles than at the bottom right where the cross-angle is finer. Along the right edge of the framed field, the fringe spacing is larger than at the center because the test line spacing grows as the lines fan out. The whole pattern and its beautiful order suggest a mysterious coded logic. The problem was to untwine the parts and to use Moiré spacing and crossing angle information to plot the path of the test lines.

Figure 3B diagrams the elements of the problem. It is an area lifted from Fig. 3A and enlarged. Off to the left is the crossing of the parallel-line systems at the angle A. There the Moiré spacing M is easily calculated and uniform.

From any RL/TL intersection point on a test line that has turned from its baseline direction, a right triangle can be drawn extending from the intersection. The triangle is made from the angle of departure Θ, the side M which runs from one RL/TL point to the next along the TL, and a base side running from the same first RL/TL point in the basic direction. The right triangle has an altitude which is equal to the rise of the TL between the first RL/TL intersection and the next intersection. The value of the rise (called D) is needed to find D.

In the larger right triangle MR that subtends Θ, the R/M ratio is the sine of Θ. Then D is the arc sine of R/M which can be used in its place. So Θ, which is Θ-A, is also (arc sin R/M)-A. Since sinΘ equals D, then sinΘ (arc sin R/M)-A equals D.

R and A have established values. So with the value of M measured from intersection to intersection along TL, the rise D from intersection to intersection can be calculated. Thus, the course of any test line can be plotted by locating the new "altitude" of the test line after adding each interval. One test line in Fig. 3A is shown to be moving upward by the calculated D stepped at each intersection. The position of the test line at any point is the sum of the D's from the basic altitude to that point.

Thus, the course of any TL can be laid out just from measurements of M. As indicated earlier the M can be a greatly multiplied value of D letting the measurements of M give D with precision.

The equation derived for this orientation and rising TL's applies as well to TL's turning down. In these the M span becomes greater than its norm (at the left). So R/M is smaller than the norm and Θ is less than A. D calculated from Msin(Θ-A) turns out negative as it should be to stop off the decrement in TL's altitude.

It was decided to find the in opera shape of the ruled line (test line) on the panel closest to the fusion line and the shape of every tenth test line from that one. These lines were labeled for reference: the first is A, the rest in order are B, C, D, E, F, G, H, and I. Those test lines are 0.200 in. (5.08 mm) apart on the test panel and include 1.60 in. (40.6 mm) of width of the panel.

On the photographic prints the intersection of each vertical Moiré line and a lettered test line was marked and each M distance on each lettered test line was measured. Each M led by calculation to the D increment. Each vertical fringe line was identified by a position number (1, 2, 3, etc.). The calculations for the course of a test line were made and arranged in M tables. The tables were designated by their origin as 6E1, 13E1, 20E1, 6B1, 13B1, 20B1.

To test the method and bring the plotted curves closer to the shape of their source (the panel), measurements were taken again after the photo of the RL's was turned on the photo of TL's to cause the RL's to descend on the TL's in the direction of arc travel. This relation is to be called the second orientation (Or. 2). In this orientation A can be called positive as the RL pivots counter-clockwise with respect to the TL around their intersection. By this rule Orientation 1 has a negative A, but the absolute value of A was used in both of the given formulas. The geometrical and mathematical reasoning, used to prove the second formula, follows the train of logic used for the first formula, although the triangles relate in a different way.
In Or. 1 (Fig. 3A) the rising TL cuts RL at larger angles and produces smaller M's. In Or. 2 (Fig. 4A) the rising TL cuts RL at shrinking angles and the M's grow. But the underlying TL pattern is still the same.

There were two reasons for going into this second arrangement and more measurements. The first was to prove that the two formulas, each used with independent raw inputs, give the same results on the same test subject; and by this to verify their authority. The close results confirmed that either formula does draw the same subject.

The second reason was to match or average the errors of the first production with a second to improve the fidelity of the results and to indicate the statistical significance of the results. This was useful in improving the results; and also in highlighting the different possibilities for error.

The most conspicuous and serious general feature was the difference in height between the curves derived...
The first effect of the pre-puddle swelling is to push weld plates apart; the slow welds do this more emphatically from different orientations. But their dips and bumps stayed coordinated in position. This was true in each of the six experimental cases.

Each case (using 6E in Fig. 5 as an example) supplies eight pairs of meaningful test line curves (A through H). Each of these eight is related to the others above and below it. The information exists, therefore, for drawing a mathematical surface of continuous change depicting the contortion of a real metal surface containing continuous change.

When test lines are picked off of such topographic surfaces and replotted, an effective recreation of the panel test lines is revealed. Figure 6 shows the shape of the edge panel test lines.

The conclusion is that the finally derived test lines printed in Fig. 6 do practically represent the condition of each of the six edge weld test panels photographed in opera. Likewise the test lines in Fig. 7 represent the in opera shape of butt weld panels.

### Discussion

The heat caused by a moving heat source on a metal panel should have a consistently typical, though complex effect on the stress on the areas around a puddle created by the source. In a weld, the expansion forces that push areas into or over the center create a combination of local compression and plastic upset. Neighboring contraction or reaction forces create a local transverse tensile stress and strain. It is pertinent to weld results to know the location and magnitude of these stresses and how they are changed by some weld conditions.

The three butt weld cases, as expected, show the movement of the panel surface inward as the puddle shrinks behind the puddle in a real weld. The three edge weld cases are the only way to show how the fusion line would move toward the center and away if it were not held in by an opposite-side weld partner.

The easiest and most agreeable phenomenon to note is the swelling of metal area ahead of the arc. In Fig. 8 all of the cases illustrate this before-the-puddle (pre-puddle) expansion. The hatching marks the area that was pushed and swelled past its original edge boundary before the puddle.

After the shading, any more area pushed toward the center is merely melted as it enters the puddle. By this the volume of the puddle increases to subsequently appear as face-and-root bead buildup. But ahead of the puddle in a real butt weld, one area actually pushes against its opposite which is pushing back. These expanding cells do push the butt edges of two plates apart.

The "unhibited" rise of the pre-puddle areas has a finer feature. The length and height of the pre-puddle expansion increases as the arc speed decreases. The wave height for the three weld speeds relate in the ratios 12/10/3. The leading swells confirm predictions made by thermal volume expansion calculations. They predicted the earlier and wider heating before and around the puddle of the slower weld, to give the greater length and breadth of expanded area.
This expanding cell is one of the three key forces that act on the material before and after the puddle. Its impact on successful welding must be appreciated. Figure 8 shows in a picturesque way the prime effect of this before-the-heat-source (pre-puddle) swelling, that is the pushing or holding of the plates apart. Much farther behind the heat source (black dot) is a representation of the post-weld shrinking area. This is represented here by elastic wires. The potential for cracking a real weld down the centerline after the puddle is apparent.

One might ask, “with the kind of tension inferred by these diagrams, why does the aluminum not crack after the puddle every time?” The answer is that the aluminum knitting after the puddle solidus freezes neutrally. At the theoretical instant of becoming completely solidified there is no stress on the solidus bridge. Steady state stresses may be imposed after S, but not in the mass before that point, for it is pliant or liquid.

The advance of a panel edge across a theoretical centerline is outstandingly portrayed by laying one side over its mirror opposite and letting the mutual advances appear as overlaps (shaded) and the mutual retreats as gaps. Figure 9 shows this effect for the three tested speeds. The sides are mirrored on the cold unchanged butt line (at the arrow), before heated volume changes have occurred. This is an artificial picture because the areas in a weld do not really overlap, or completely intrude into upset and then retreat elastically. Still Fig. 9 helps to show with special forcefulness the progressive differences between the 6, 13 and 20 ipm weld speeds. The area over the puddle is treated here and in the next several illustrations as a kind of hole. It will be an unshaded area bounded for convenience, in front by the forward solidus, in the rear by the after solidus and on the sides by the B test line.

The one should be kept in mind that the edge of the panels will be described as the panel’s butt line in the discussion. But, in fact, it is the A test line, from the Moiré prints, the line that was the last visible line on the panel’s photographed surface.

The relative swelling ahead of the puddle stands out strongly in these illustrations but the point of the maximum transverse imposition (P-peak) is now clear. With increasing weld speed the peak tends to clearly lag the arc more. From 6 to 13 to 20 ipm the expansion lags the arc center from 0.207 to 0.680 to 0.744 in. (5.3 to 17.3 to 18.9 mm). The total area of overlap diminishes clearly while the peak height increases slightly.

The two sides, if physically forced apart by the pre-puddle swelling, take on the appearance of Fig. 10. This
picture is a degree more realistic. Real weld panels actually are separated by this phenomenon. The high points holding the plates apart lie before the arrow points. The error in this illustration is that the leading nodes are not rigid but somewhat plastic.

That the peaks of expansion (P) occur early in the 6 ipm weld, and late at 13 and 20 ipm is made more evident in Fig. 10. The continuing transverse growth is evident at 13 and 20 ipm where the overlap increases after S.

At 20 ipm the expansion retreating momentarily after the pre-puddle node rises again to a peak height much greater than the pre-puddle node. Then the area retreats swiftly. Tension "wires" across the gap are meant to be reminders that true welds have forces drawing and holding these edges tightly together. These have the effect of increasing the compressive load at P in real welds. The 13 ipm specimen differs only in that the rise of the after-puddle peak is not so much higher than its pre-puddle node and that its retreat is gradual.

The 6 ipm specimen is unique because the peak of expansion (P) occurs before the puddle solidus (S). This means that the puddle in the 6 ipm weld swallows without resistance all the inward transportation of aluminum area. That is not different from the 13 and 20 ipm welds which also swallow whatever can move across the puddle boundary. The difference occurs at the rear of the puddle (S). Here and after, the heated sides pull area away from the centerlines. In the 13 and 20 ipm welds, the metal expansion seen after S continues to drive area into area, causing increasing compression up to P which lags S by notable dimensions, about 0.430 and 0.490 in. (10.9 and 12.4 mm) respectively.

The status illustrated by Figure 10 can be modified to express, closer to reality, the stresses after S. As said before, movement into or out of the puddle merely changes its liquid volume. But after the point of solidification any transverse motion generates a change and stress. So the edge profile should be translated to start at S to show the progress of upset/stress after S as in Fig. 11. Here the position of two plates is defined by the pre-puddle swelling but transverse effects are added only after S. This is not an illusion. It is a true graphic representation of the volume changes after S.

At 6 ipm only material retreat occurs after S, so tension starts out of the solidus. This is close to the customary view. Its interesting to note that one might expect that the larger forward swelling supports the tension after S. But tension starts at zero at S in all cases without regard to the magnitude of the "constant" swelling. Tension is related to how quickly the sides pull away later and how soft the pulled material is. Cracking is "exceeded strain limit" (for a temperature). The magnitude of forward compression should affect aft tension or cracking if it suddenly increases as:

1. When a weld gap suddenly closes.
2. The material thickens.
3. Current is suddenly increased.
4. Speed is suddenly reduced.

On the high end of the speed scale, toward 20 ipm (Fig. 11) a different force becomes primary. The highest points of expansion turn out to lie after the puddle. A side's growth (0.0038 in., 0.097 mm) after S is greater than the growth before (0.0015 in., 0.038 mm) which almost could say the parts will be separated by the P's and will gap ahead of the puddle. But the P's are soft to a degree based on their temperature. The question is whether the peak of expansion can be so intense and stiff as to strain the solid material after it is past its strain limit.
The 13 ipm appears to have such a modest peak, slowly reached and slowly left as to suggest an optimum condition which it seems should be a long compression on a solidifying bead and fusion line.

The prime conclusion taken from these constructions is that the post-puddle aluminum alloy normally experiences a transverse compression.

Once this idea is considered, it becomes easier to realize that this must be so. Aluminum alloy at solidus temperatures has the “strength” and consistency of cottage cheese. One can assume it probably does not have ability to resist tensile stress at all. The metal just after the tail of the puddle must experience compression, zero load, or only the slightest tension, lest it crack. From this point of view, alone, the tensile stresses ordinarily assumed there should be doubted.

Discussion now moves into more subtle aspects of this apparently substantial phenomenon. The finer differentiations that show up with change in welding speed help to further understand the phenomenon. More importantly, however, they show the potential for controlling the weld bead solidification-and-hardening process for an effect on defect rate.

Wherever the edge lines of one weld speed are laid onto the same-speed butt lines, a family relationship is evident. The rise of 6B occurs earlier than the rise of 20B as it was in the edge lines. Figure 12 presents for each speed the edge A lines (marked by A) superimposed on the butt A lines (the continuous heavy line). The most significant disparity in each case is the failure of the edge peak to rise to the height of the butt “peak.” It could appear that the butt line was pulled toward the weld bead, but another mechanism will accomplish this effect more convincingly.

Note that the A line of the edge weld tilts down after, in every case. This can be explained by the hot area around the arc pushing the straight panel out of line. In a butt weld the first new phenomenon has the weld holding in the late tail end of the A line. The late restraint must be tensile. The first correction to A is to bring it to A‘ by that restraint. This is helpful but does not make up much of the disparity.

What now is obvious is that the volume that wants to expand is pinched and forced to extrude in the
direction of lowest resistance, roughly toward the puddle and post-puddle areas. A similar mechanism was used to illustrate the effect agreeably and find some magnitude for the effect. The panel "tail" was mathematically pulled up by enough degrees (Q) to make it parallel to the weld centerline—Fig. 13. A special plastic area was defined. It was a triangle with an apex angle located on the 400 F (208 C) isotherm and its base along the length of the puddle.

When the A line in Fig. 12 is lifted by Q, the triangle is pinched. Its area kept constant has its length increased. By adding this limited increase to A' (calculated for each speed) in Fig. 13 and holding it, the shift of A is rationalized to A'. At 6 ipm this increase covers one-quarter of the missing difference between the edge and butt A lines. At 13 ipm it fills all of the difference between the lines and at 20 ipm half the difference. This logical and appropriate model is not incorporating the real wider expanding area but its point is clear.

In truth, and in a more direct form, the bulge inward (which is captured and held) is the sum of transverse and longitudinal expansion (area) which can be manifested only inward into filling the puddle or upsetting the soft post-puddle metal. The post-puddle metal at 6 ipm appeared earlier to experience retreat (tension). But material pushed in by expansion and longitudinal constraint might offset and overcome that shrink. The inward extrusion instead of being resisted would be attracted, which in the net would increase the transverse metal transfer. This is a subject worthy of more intense study. It is, after all, the site of the strength-forming events and all the forms of weld cracking.

A good way of detecting the form of stress across the weld plate is to measure the change of space between test lines (TL's). At every position the increase or decrease of the span between A and B; between B and C; E and D; and the rest was noted.

The word "increase" means purely the enlargement of the span dimension as seen photographsically. Increase is a positive change of dimension. It can appear from plastic strain, elastic strain, thermal dilation, or a mix. Likewise decrease is a manifestation of plastic and elastic compression and/or thermal shrink. The distinction is important to make for understanding the results. It is possible to see a decrease and attribute it to thermal shrink instead of compression. These components can be approximately separated. Elastic strain is likely to be measurable but quite small and distributed over a wide and colder area. Thermal dilations could be calculated and subtracted to leave essentially plastic movement.

The AB band near the puddle was most susceptible to plastic change and the BC band a grade less. In the edge cases the activity around the puddle has a character repeated in each of the three speeds. In AB the width clearly decreased beside or after the puddle. BC bulges where AB pinches in each case.

At all speeds BC's expansion of 0.0035 in. (0.09 mm) occurs close to the position where temperature would probably give it a 0.0030 in. (0.08 mm) additional breadth. But the failure of BC to return to the width it had before the arc indicates a permanent increase—that is, when its breadth shrunk thermally, it was stretched mechanically.

Whereas, the edge band widths maintained a family similarity while shifting form slightly from 6 to 13 to 20 ipm, the character of the butt band width changed between 6 and 20 ipm. The 13 ipm is in between, marking the step in the transition.

In the 6 ipm butt weld the band increased through position 12 from which it decreased slowly and slightly by an amount that could be attributed mainly to temperature subsidence.

In the 20 ipm butt weld the clear BC peak (at position 12) attributable to thermal expansion corresponded at the same position with a large decrease of neighboring AB, making a case here for the squeezing of AB by the transversely growing BC, supplemented by CD and the others.

The idea of overlaying an edge specimen test line on its counterpart butt specimen test line (Fig. 13) was not useful for scaling stresses in the butt
specimen. This was due in part to the turn of the line. But butt surface change through the puddle compared to edge surface changes by comparing only the band width difference. It was stated earlier that an area which changed in the unstrained edge specimen but did not change in the butt was being stressed in the latter. For example, an expanded field in 6E would be a compressed field in 6B, where it is held in on all sides. So a strip width of an edge specimen (such as the band enclosed by test lines A and B) is different on the butt specimen by a stress difference existing in the latter. The differences are shown by position in Fig. 14.

When the value of the AB band width of the 6 ipm butt specimen was greater than the value of the edge specimen's AB band width, tension across the butt's AB band was designated. This procedure has some useful attributes. The most obvious is that band width changes due to thermal expansions or shrinks will be nulled. Presuming that the isothermal pattern for an edge specimen is the same as for the Butt specimen, the thermal change of a point on one will equal the thermal change on the other, and subtraction of the two gross dimensions will leave only the evidence of stress-induced strain.

The effects generated at 6 ipm are seen in Fig. 14. The cold original band width is a constant 0.200 in. value drawn as a straight horizontal line. The continuous line whose height represents the butt's band width is, from the puddle and after, larger than the reference AB 0.200 in. band width. The dashed line representing the corresponding edge band width is smaller than the reference AB width. The two lines mark out the clear differences between them. The difference was marked as tension in the butt surface encompassed by AB.

The 20 ipm effect is also clear but different. The edge's AB band width is close to the reference AB width saying that the edge's AB band width was little changed from its original condition. The reduced width of the butt's AB band, however, is distinctly different. It has a large decrease from the reference width. The butt's band width marks its transverse compression. Although longitudinal stretch of the butt's band is an alternate explanation, that effect would have been seen almost as emphatically in the corresponding edge's band width; so it is not considered.

The shaded "tension" lobe for 6 ipm grows from position 6 through 11, then remains constant through 16. The position of the 20 ipm span is the most plastic area; above 600 F (or 316 C). Tension, though symbolized by the entire shaded field, is in fact only demonstrated by growth, which only occurs from 6 to 16. The constant next period is outside of the range to significantly progress, either because it lacks stress or it is too cold to react visibly to existing stress.

The "compression" lobe of the 20 ipm case indicates a band-pinching stress on the butt's band between 10 and 13. A constant state exists from 13 through 19, followed by a significant butt band increase which could indicate a tension stress on the butt surface.

The lobe widths are intended to mark stress-caused strain existing on the butt specimen surface by any position. The width actually is the accumulation of strain adding from the left. So each increment of relative band width change represents a reaction to stress. When the lobe width stops visibly changing, either stressing has ceased or the material has hardened. Therefore, the measure of stress will be found to be the change of the lobe width along the position scale. This can be represented by ΔN/ΔP. This is the rate of lobe width change. The rate value is plotted in Fig. 15.

The information exposed by Fig. 15 is remarkable. At 6 ipm each positive value represents an apparent positive transverse strain of the AB band on the butt weld. AB grows at an increasing rate up to position 8. The strain continues but at a diminishing rate until it stops at 12. Effects after that are small and not clear. This AB width increase will not be called clearly transverse tension. The "wedge squeezing" phenomenon outlined in Fig. 12 has as a product the expansion of transverse dimensions and the compression of the mold. The best explanation for expansion before and across the puddle, as well as after it.

The 6 ipm weld speed was where one has been tempted to claim transverse post-puddle tension. The condition at 9 finally challenges that assumption there as well. Although transverse retreat from the center is indicated, the longitudinal squeezing can keep the area overfilled enough to maintain a transverse compression sign on the centerline.

At 20 ipm the expansion over the span of the puddle (7.5 to 9) is explained by the "wedge squeezing" argument. The determined reversal into a pinched AB band where it virtually necks at 11 and continues to decrease up to 14 is explained as compression. This would be the compression created by the lapping thermally swelling surfaces outside of B. In order to squeeze AB as suggested, the swelling outside of B has to significantly exceed the shrink value which is being reached across the bead inside of A.

The AB decrease after position 20 is a slightly inconsistent and significant mark of tension in the butt surface although the alloy is quite cold. If the values are true the strain is 1%.

The information appears to portray the real situation. The revelation is of greatest importance in correctly understanding the weld solidification-and-hardening mechanism in aluminum alloys and perhaps other alloys as well.

The data documented by Fig. 15 and described in the text above can be expressed in a clear mechanical analogy. Figure 16 gives a faithful sense of the difference between the post-puddle experience of the fast and the slow weld, and a summary of the most important event revealed by this paper.

Note the similarity of the shape of the fusion and the A lines (and, in truth, the others) of both speeds. But, note well that the longitudinal forces of the slow weld dominate the molding of a hypothetical square because of the weakness or absence of transverse resistance. In contrast the fast weld has a large transverse compression force that overpowers the reliable longitudinal compressive forces to mold (really) the square differently.

Consider which condition is best, what a transition speed promises, and what changing the magnitude or position of the stress coordinates will do to weld quality or weld properties.

If these unusual results after the weld puddle had no effect on weld results, they would represent an excellent academic curiosity, a study worth summarizing and common practices.

According to the work discussed here, the temperatures chosen for aluminum alloy testing are:

1. Probably too high, as tension seems to come later than usually assumed.
2. Correct for one welding speed but not for another as the tension stress moves to different positions with different weld speeds.

But the interest of this work lies in questions about the relative quality of welds made with the compression-and-tension transition in intensity and position. Although weld strength might be related to coherent changes in that situation, the work described in this paper was done to prepare for organized studies in affecting the incidence of weld imperfections.

The results of this work show that
Stress from Outside of B

Fig. 16—In this mechanical analogy the nature of the difference between a fast and a slow aluminum weld is faithfully summed. Two sets of data have been revealed by this study: (1) transverse tension in slow welds, transverse compression in fast welds, longitudinal compression in all welds; and (2) transverse broadening of material aside of the slow weld, narrowing aside of the fast weld. In spite of the sameness of the fusion and A lines of the fast and slow welds, these data point to an extraordinary difference in the continuous wrenching of the weak post-puddle aluminum next to the fusion line.

The travel speed is a highly weighted operative on the disposition of post-puddle stresses; as such, it should be an influential instrument for coherently changing those stresses to affect the tendency of a weld to misbehave, particularly to crack.

With the current state of welding art, there are too many permutations of weld conditions and too little organized knowledge of their inward effect on post-puddle metal for anyone to simply design a combination that produces an optimum result. Still, welders and welding engineers know where the end of each useful range of each variable is. It shows up as a catastrophic failure within a few length units of welding. An obvious example is heat input. Too much current and the weld bead sags, undercut, and cracks with noticeable tre-

Conclusions

1. The Moiré-photographic system can reveal, at meaningful levels, the turns and strains of areas on panels being heated or welded by a moving heat source.
2. The Moiré system shows that the disposition of temperature rises causes a distinct profile of transverse expansion whose usual feature is a peak after the weld puddle.
3. As welding speed shifts from 6 ipm (152 mm/min) to 20 ipm (508 mm/min), the peak location shifts from over the weld puddle to 0.744 in. (19 mm) after the puddle.
4. This peak should result in transverse compressive stresses in that location on butt welds.
5. This compression in faster welds should shift and intensify the post-weld tension which follows much later than traditionally assumed.
6. Data suggest that much of post-puddle expansion and consequent transverse compression is attributable to the pressure of longitudinally compressed material beside the weld bead.
7. The coherent change of this pattern with change in weld speed suggests that there are experiments that will relate a weld's cracking tendency to weld speed. The problem of welding research and technology is a heady one.
is to create a high enough crack incidence environment so that differences from speed differences will be measurable in a practical quantity of specimens.

References

Technical Note
(Continued from page 262-s)

Fig. 1—Typical microstructure of base material.

Fig. 2—Crack path within the heat-affected zone. Note intergranular mode of linkage of tears and cracks.

Fig. 3—Typical fractograph of V-notch specimens broken at -100 C (~148 F) in three point bend test.

The authors would like to express their appreciation to Dr. S. Ensha for his valuable discussion with respect to this work.

Acknowledgments
The authors would like to express their appreciation to Dr. S. Ensha for his valuable discussion with respect to this work.

References