THE EFFECT OF WELD STRESSES ON WELD QUALITY

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INTRODUCTION:

A narrow heat source raises the temperature of a spot on a solid piece of material like metal. The high temperature of the spot decreases with distance from the spot. This is true whether the heat source is an arc, a flame, an electron beam, a plasma jet, a laser beam, or any other source of intense, narrowly defined heat. As soon as the heat spot moves, the thermal slope on the forward side becomes steeper, while the trailing side stretches out behind it. This can be seen in the two examples in Fig. 1, where temperature is shown as altitude on a three-dimensional plot.

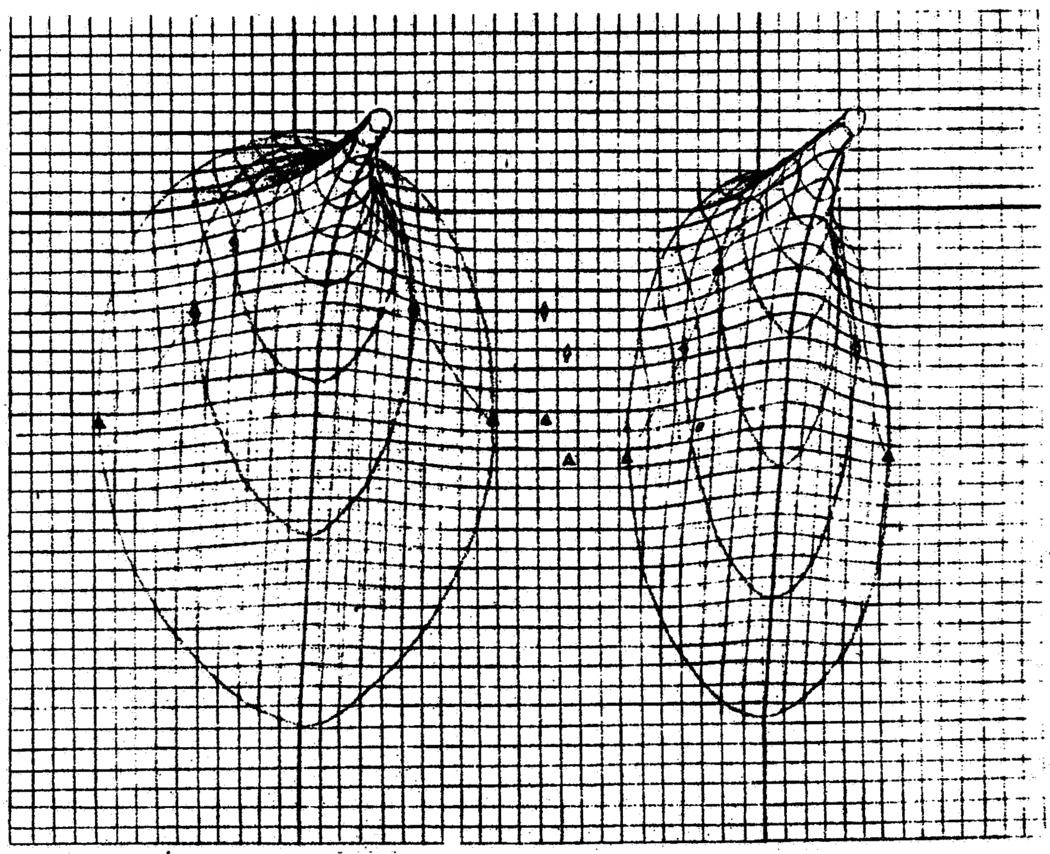


Figure 1 - A slow weld (left) on 2014 T6 aluminum compared to a fast weld shows three notable differences on the isothermal maps: (1) broader flatter gradients, (2) greater temperature rise ahead of the heat source, and (3) less lagging by the heated system.

Advantage is taken, in this discussion, of comparing the qualities of slow welding (6 inch per min.) with fast welding (20 inch per min.). Several, simple differences of degree are visible as the speed of the moving heat increases: (1) The sides of the faster become narrower and more steeply sloped; (2) The bow wave of heat, i.e. the temperature rise over an area preceding the heat source, becomes lower, shorter, and narrower; (3) The general mass heating lags the source more, as suggested by the swept-back lines that mark the points of peaking temperature. This signifies lagging by a kind of thermal-expansion center of gravity.

The isotherms illustrated here (the ellipsoidal topographic lines) can be found by experiments or by calculation; but only calculated curves such as these can describe conditions smoothly right up to the puddle edge. It was the growth of strips defined under these isotherms that led to the understanding of the patterns to be described.

The theoretical construction followed by some experiments precipitated an image of a coherent pattern of stress fields around a weld arc moving on metal sheet. A series of subsequent experiments reinforced the sense of the fields operating where expected. The evidence points toward stresses imposed across the center line (transverse to the weld line) but changing several times. First, compression ahead of the puddle gives two effects: a force pushing the plates apart and plastic upset just before the puddle. General heating of material on both sides of the puddle pushes the material without resistance into the puddle. This is responsible for subsequent shrink and for the bead thickening. Tension appears across the mushy zone as expected. Compression can be found at higher weld speeds just behind that because of a lag in the area's gross expansion aside of the heat source. It has two effects: a plastic forging effect on the just-cast aluminum, and a holding of the sides apart that can increase the tensile strain of the last stressed zone which comes essentially from the shrinking of local area in the center of the surrounding greater expanse of rigid material. Longitudinal stresses are simpler, but they still add significantly to bead thickening and thereby to transverse shrink and residual stresses.

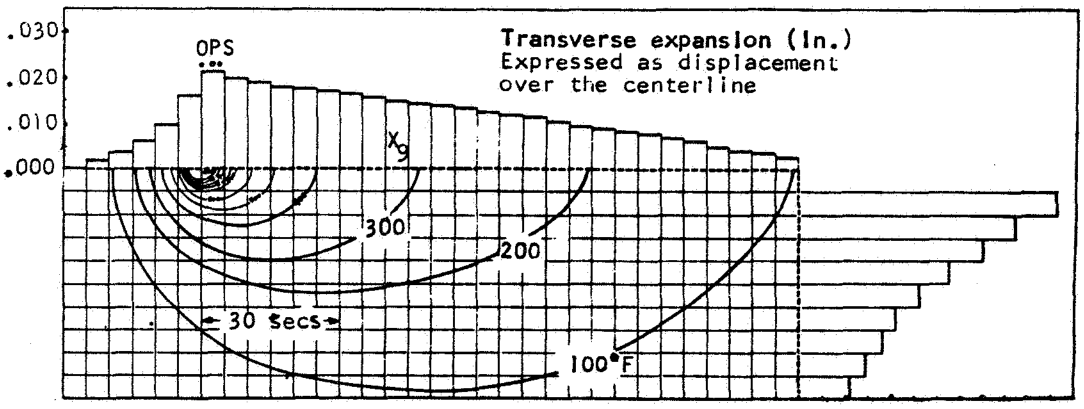
These stress events can have their intensity and extent changed coherently with changes in the simple and most available instruments: weld speed, hold down, gaps, tacks, and others.

The work started on theoretical grounds and moved as far as simple theoretical rigor could take it then shifted to a deductive and reasoning system to uncover the location and order of the various fields of stress. At the end, a variety of experiments added up to some proofs that the identified stresses existed and in the order described.

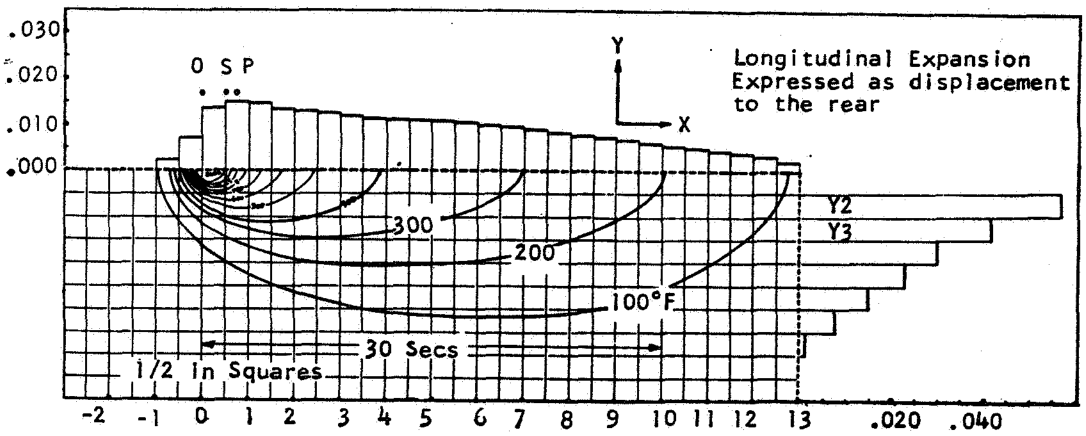
The work was originally undertaken to determine the reason for cracking in the 2014 welds. The simple pattern to be described and illustrated provides the rationale behind the varying stresses in other alloys as well. It appears to provide a simple format for the seemingly confusing deformations-and-stresses interplay on any material experiencing a moving point heat source.

METHOD OF EXPERIMENT:

The isotherms in Fig. 1 were calculated and drawn for a 6 inch per min. moving heat source and the 20 inch per min. heat source, with the heat input in each case sufficient to make a fused zone 0.8 inch of an inch wide (The detailed paper covering much of this development can be found in Ref. 5). Strip models were built as shown in Fig. 2 which in effect sum the volume increase under each area increment of heated aluminum. The growth of the horizontal (longitudinal) strips are expanded to the rear. The vertical (transverse) strips are increased so as to project expansion over the centerline of travel.



a) Heat Source Moving at 6 ipm



b Heat Source Moving at 20 ipm

Figure 2 - Calculated isotherms and strip expansions caused by moving point heat source, moving at 6 or 20 ipm, with heat sufficient to each case to produce a 0.8 in. wide bead in 0.250 in. thick aluminum alloy. Note how Peak expansion on the faster weld has come to lay behind the solidus.

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The first categorical difference between slow welding and fast welding is evident. Because of the more trailing isotherms in the faster weld, the peak of the integrated expansion appears to have fallen behind the solidus. The effect of this, however, is more clearly shown in Fig. 3 where a rule change is made at the point marking the solidus. The L_1 line marks the profile of transverse expansion, and should in its way mark the creation of stresses.

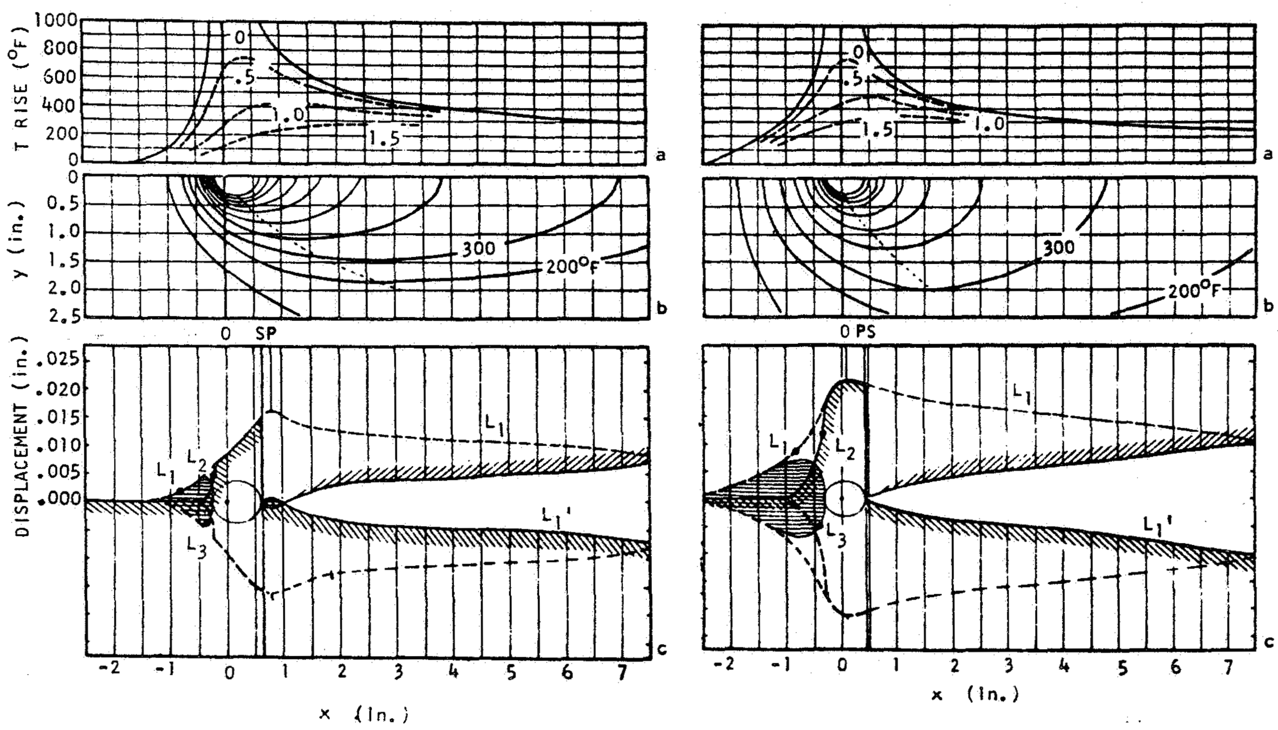

Figure 3 - Note how the changes in transvers expansion after the solidus in the fast weld (left) may create compression and upset.

Ahead of the puddle this obviously means compression and expansion that should push two plates apart. This is clearly very much larger on the slow weld that has a large bow wave of heat. Soon the puddle will absorb all of the material that intrudes into it from the sides and without back pressure or stress resistance. But with solidification at the back of the puddle, changes in strip length will again produce stresses instead of uninhibited movements of material. Now it can be seen clearly, if the L_1 profile is transferred to the L_1' position, that height of strips changes after solidification must result in compression where the vertical strips intrude and tension where they retreat. The fast weld then experiences compression and upset before the general recession. The slow weld (on the right) has its strips receding from some point starting inside the puddle, which is the conventional view of weld cracking. The illustrated after-gaps can exist in fact or in the form of tension concentrated toward their forward end. This ended the more rigorous mathematical and physical description of events acting across the travel center-line.

The effort to understand the meaning of this information and the many anamolies appearing in the laboratory and the shop nourished the next phase of this investigation that attempted to complete the pattern and interpret welding experiences. The final results are summarized figuratively in Fig. 4.

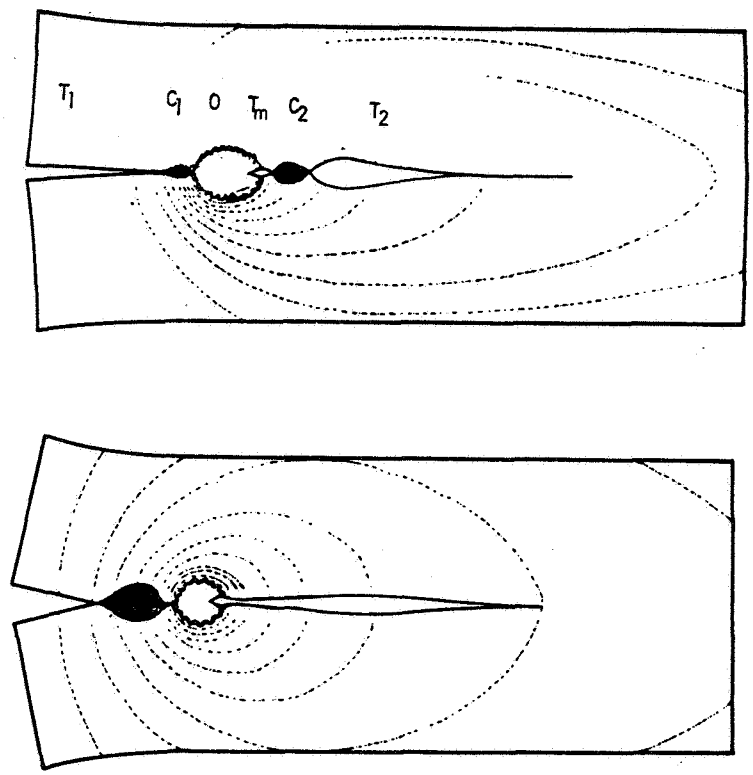

Figure 4 - Five transverse stresses may operate on the center-line of a weld, as marked on the fast aluminum weld above. With slower welding one compression field disappears and the two aft tensions coalesce.

A variety of experiments, (noted in reference 2 & 5) were studied for their relation to the mathematical and graphical expressions of Fig. 3. They consisted of specimens on which distortion or shrink or strain was measured as a moving heat source traversed the length of the part. The welding produced very graphic illustrations of the forces at play in certain locations. The changes in strain or in geometry of these specimens was consistent but it had heretofore eluded explanation. With the laying out of the characteristic stress pattern, the strange behavior of specimens did indeed fall coherently into place, and thereby became some proof of the validity of the revealed pattern.

DISCUSSION:

The Character of Stresses Around a Moving Heat Source

Proof of the following stress status will be avoided in this paper for the sake of brevity and because the theme to be emphasized here will be the effect of these stresses on weld quality. It is most important though to set the pattern firmly in mind. The basic pattern of forces acting on the center line is most completely illustrated by the fast weld in Fig. 5. The bow wave of heat preceding the puddle tends to push two plates apart at C_1. This creates tension or a gap ahead of it, in reaction. The puddle can bear no stress at all. The liquid to solid phase change in the mushy zone does create an operating tension (Tm). But after the

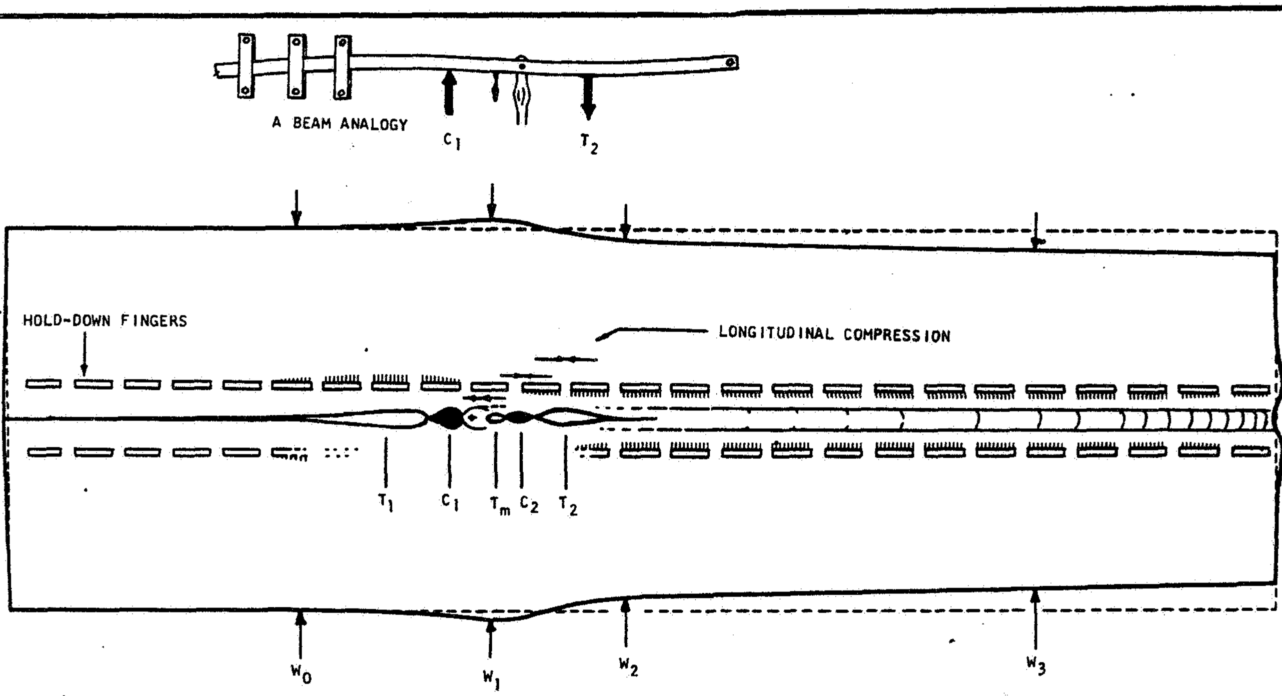

Figure 5 - In a steady state fast weld on aluminum alloy it should be possible to find the work pieces spread (T_1) because of the push-apart force (C_1) caused by the temperature rise and swelling ahead of the arc. After the arc, effects combine to give transverse tension (T_m), compression (C_2), and a general recessional tension (T_2). But longitudinal compression is found alongside the arc and lagging at points further from the centerline. Several shop-available instruments can be used to reduce or reproportion these stresses.

solidus the expanding outer isotherms tend to push material toward the centerline so as to more than make up for the shrinking value at the centerline. This creates a compression. But soon the general recession, that is shrinkage over a wide area, soon requires tension across the whole specimen. The rigidity of the outer area prevents this tension from being satisfied by an inward bending of material. This reaction alone indicates the necessity of making weld specimens out of wide parts when an experiment's purpose is parameter optimization or weld strength or stress determination. It is clear that narrow specimen plates will deflect outward and inward as the heat wave passes and they will never allow great stresses, normal stresses, to rise across the centerline.

The existence of longitudinal stresses is simpler to understand. They are in fact peaks of compression which occur at the peaks of temperature rise in each horizontal strip. It is important however to note that the longitudinal as well as transverse compression vectors cause an transverse extrusion of material into the soft plastic-and-liquid puddle area sink as it passes. This causes greater bead thickening, weld shrinkage, and residual stress than simple (transverse) calculation will predict.

Now some illustrations of how this train of stress events operates in common situations will serve to set the pattern in mind and to introduce ideas of how these stresses affect weld quality.

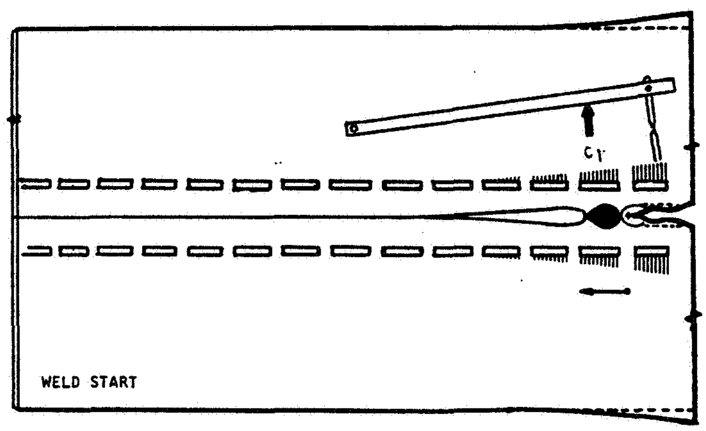

Figure 6 - The normal push-apart force (C_1) of the advance heating exerts an extraordinary stress on the short length of weld which exists at the onset of welding. This applies no matter where on the piece the weld is started. Strong hold-downs and those extending far to the rear inhibit the motion of the parts and so reduce this tendency.

Wherever a weld starts, (Figure 6) the bow wave of heat that precedes it, although of ordinary magnitude, has the power to render the initially short length of material behind it. C_1 then can push two plates apart sufficiently to tear a short length of weld that may be complete. Tacks are usually sufficient to preclude the beginning of this kind of event.

In contrast (Fig. 7) as the heat source approaches the <u>end</u> of a piece of material, the heat wave preceding the puddle grows to extraordinary proportions when the dam formed by the end of the metal prevents the heat from running forward into wide areas.

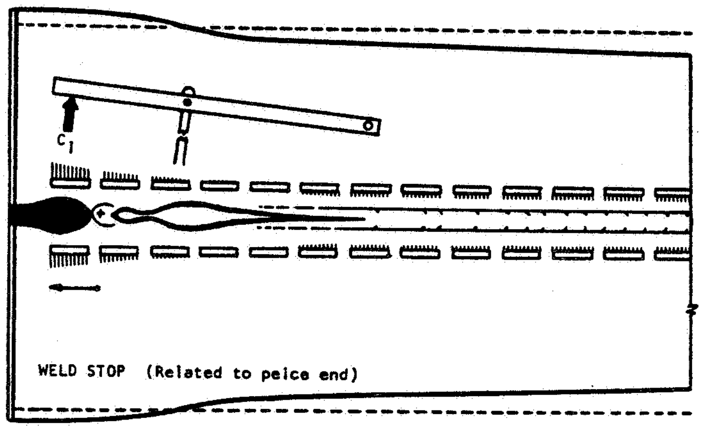

Figure 7 - As the heat in advance of the arc approaches the end of the work piece it can no longer run forward so it builds up higher and over a wider area. This gives C_1 an extraordinary push-apart force that stretches the after puddle area to an unusual degree resulting in cracks near the end or in diminished weld shrinkage.

This causes an extraordinary growth of temperature and expansion (which means the C_1 force reaches an <u>extraordinary</u> peak). When this occurs, it produces an extraordinary tensile strain and sometimes cracks after the puddle. This unusual event is manifested also as a flare in the width of the work as illustrated. When C_1 becomes very hot as the puddle moves more towards the end, it becomes plastic and diminishes as a force. If the weld is terminated near the end, extraordinary tension will ultimately grow across this upset region. A bridging tack may aggravate instead of cure this problem. It should be noted here that there is a part widening at the start of a weld caused by stretching of the aft material and also at the terminus of a weld caused by stretching of some distance of aft material. These do increase the width of the specimen in these locations. If the weld represents the longitudinal joint on a tank, it creates a flare on both ends of the cylinder. If the weld start and termination point are not consistent and the trim-off cut is not consistent tanks produced with the same weld parameters will <u>appear</u> to be highly variable in diameter. But in fact the span <u>between</u> these end transition situations is very constant in its weld shrinkage and tank diameter, from point to point in a tank, and tank to tank in production.

In the case of a circumferential weld around a tank or tube no end of the material is reached, but rather a tie-on to the previous weld is made. When the heat source comes upon a tack or the prior weld as it does in the circumferential weld of a tank or tube (Fig. 8), something else happens. Ordinarily the C_1 force pushing plates apart creates a small gap ahead of the heat. But when the system approaches a prior weld gapping cannot occur. C_1 then grows as a force because of the failure to spread and flex its members. This force puts extraordinary stress on the end of the approached weld or tack. Often the force can crack the prior weld. Furthermore as the puddle approaches the rigid bridge the upset at C_1 increases and then the extraordinary upset area experiences extraordinary tensile strain when the heat passes on. This extraordinary strain can turn to cracks in that location.

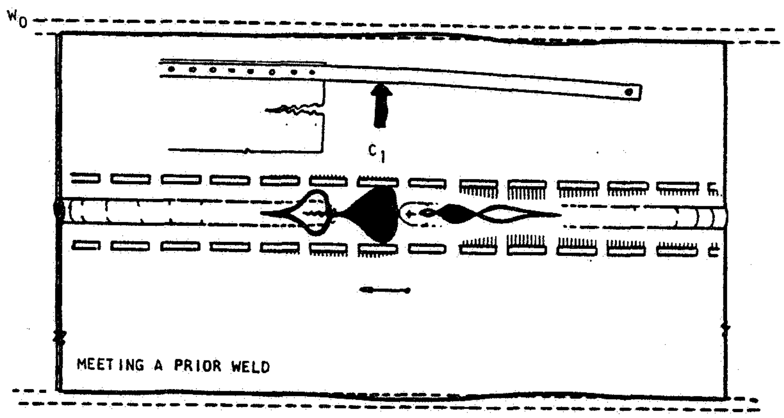

Figure 8 - The rigidity of the prior weld causes the normal forward expansion (C_1) to give extraordinary effects: (1) the push apart force may become high enough to split the prior weld, and (2) the upset in the plastic zone grows larger to require an extraordinary shrink in that location when the heat source moves on.

In the previous three illustrations, it can be seen that the force of C_1 has had undesirable effects on the after-puddle material. That force of C_1 can be diminished by the filing of a gap into the butt lines where C_1's force must be decreased. Instead of the members being spread by the arrival of C_1 at the critical point they will remain unflexed as C_1 only fills some space with its swelling.

Cracks are undoubtedly due to tensile stress of the wrong magnitude occuring at the wrong temperature. Since some of the tension after the puddle is due to the forces exerted ahead of the puddle, any device for reducing this tension ahead of the puddle, could cause an alloy that has post-puddle cracking problems to do better. So it seems conceivable that welding on a gap such as shown in Fig. 9 would keep down the magnitude of C_1 and thereby keep down the magnitude of T_2. Welding onto the right size gap can create just the right T_2 conditions by adjusting C_1 to a specific magnitude. In this way it may be possible to successfully join an alloy which is unweldable because it always cracks under normal shrinkage strains.

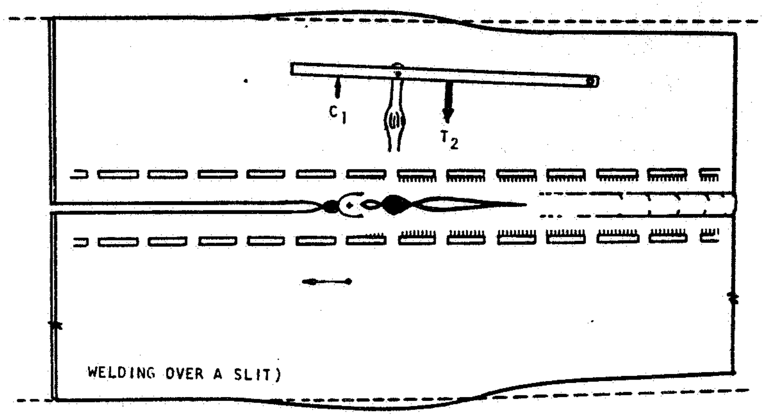

Figure 9 - The normal push-apart force (C_1) is diminished when the forward swelling moves only into a gap. This reduces net tension in the after puddle areas diminishing certain forms of cracking.

Changing Welding Stresses

There are many ordinary instruments for producing extraordinarily successful results such as welding the unweldable or as easily welding the difficult-to-weld. Introducing a local gap to compensate for a local problem is one instrument. A specific constant gap or tapered gaps are others. The difference between a closing gap and an opening gap is remarkable. Welding into a closing gap greatly raises and shifts forward the general after-tension. Welding into an opening gap has the opposite effect. This suggests that generalizations on residual stresses are tenuous, no matter how carefully the ex post facto material is scribed and sliced on the laboratory bench, when such vital conditions as gap, travel speed, and the others are not specified.

Of course, the instrument of change most vital and most easily altered is travel speed. At a very slow speed tensile strain across the solidus and the most sensitive after areas is great and usually damaging. Increasing the speed tends to move the tension aft further from the liquid into hot short regions. By gradually increasing weld speed the maximum tension can be made to act across positions farther and farther after the solidus. It can be seen that this tension can be placed deliberately over a selected temperature-structure or it can be moved off of a particularly sensitive point. Indeed it always should be.

There is evidence on the 2014 aluminum alloy that damaging stress diminishes from 6 ipm to 13 ipm to rise again with higher speeds. It may be that at first the tension is moved back beneficially from a most sensitive hot short region but that with faster speeds the magnitude of peak-tension-stress, rising, becomes so great that it imposes damaging strain even on the later sturdier metallurgical structures.

In connection with this, the exotic attempts to influence stresses and structures by point heating or cooling must take into account the coherent thermal-and-stress geography of the part lest they sink into a sea of contradictory results.

For example, the effect of moderately heating and expanding C_2 would be deleterious by increasing the tensile stress imposed at T_2. Yet by either moving the concentrated heating .6 inch back on to T_2 to relieve tension or by increasing the heat to turn C_1 plastic reducing its push-apart strength gives opposite salutary results. Similarly, cooling after the weld can produce harmful or salutary results depending on its location within an inch. The coherent pattern is vital to predicting the consequences of heat added or subtracted from point on a part surface.

In almost every case hold-downs —their force, position, and chilling quality— are not appreciated for their effect on the puddle, the solidifying weld, and the integrity of the post weld structures. Yet it is clear now that a row of hold-down fingers such as in Figure 5 (or in Figures 6, 7, 8 and 9) can have first order importance on the stress balances (nicely exemplified by the beam-lever analogies that are shown). A heavy hold-down force by the fingers of Figure 5 will counter the push-apart force C_1 puts on the plates and thereby reduce the aft tension ordinarily imposed. On the other hand too much force causes the expansion of C_1 to convert mainly into centerband upset. And then after the puddle passes when general shrink requires the material to go back out then the more thickened bead may split instead of stretch. The closeness of the hold-down line to the weld edge also influences the see-saw balance of the prime actors, C_1 and T_2, and the other three also, since it tends to isolate the volume changes and stresses that lie between the hold-down lines from those outside. If nominal status is unrestrained material then the most abnormal situation has heavy hold-downs very close to the bead edge. Neither is optimum for that lies under a certain travel speed with fingers of a specific load placed at just the right position between zero and infinite distance from the weld. Inept choices increase warpage, cracks, porosity, and the need for more variation in parameter values in the course of the weld.

The degree of heat that shunts into the hold-down line produces effects similar to the mechanical restraints. They are especially significant when the alloy welded is of low thermal conductivity and the hold-down material is high. Since the heat sinks in the hold-down line there is little temperature rise or expansion beyond the lines. Any of the inwardly directed effects (good or bad), produced by the usual expansion in the outlying areas, are missing.

A philosophical point should be made here. These are significant influences, but complicated because of the multi-weighted balance that exists. Yet they cannot be ignored, because these instruments are commonly acting. There is too great a likelihood that they are by chance being misused to cause trouble. They should be rationally used to ward off trouble. Since these devices form every welding situation, it behooves every technician to become their master. All that needs to be acquired for this is understanding.

The theme carried through the last few paragraphs has dwelt on how to use the conditions that influence welds to diminish the level of defects that may be a norm. In other words by recognizing the importance of these conditions and choosing their value wisely the threshold of success can be shifted. The usual instruments for bringing this about —better tools, more precise power sources, more cooperative alloys; all well worked subjects— are not part of this discussion. The specific instruments discussed here, although varied, are all related to one common frame of reference: their push and pull ahead of, over, and behind the heat source. So little of the tortuous experience of the material is visible that this field has not received its proper ranking in importance, and its position may be prime. Certainly aluminum welds suggest this more emphatically.

Welding Stresses and Weld Quality

Consider now a theme that has a different slant. Instead of looking to shifting the thresholds in order to lower stresses and diminish average defect incidences examine for a while some unfortunate symptoms that dot a welded product. Many of these anomalies can be explained by tracing back across the territory of the dynamic-stress logic to find their cause.

It was during some pre-activation experiments of a large vertical aluminum welding fixture that it was found that the population of almost every kind of weld defect increased close to a gap dimension change. Cracks, porosity, lack-of-penetration, burn-thru, and distortion showed distinguishable rises in population in areas within 5 inches of gap changes. The explanation reveals one of the most interesting and significant sources of those problems, and also uncovers the relevance of the stress factor.

Starting with Fig. 9 imagine the weld progressing on a gap of a constant 0.010 inches. A natural balance exists between the largest forces of C_1 pushing the plates apart and T_2 pulling them together. T_2 is naturally under a tensile strain and yielding, to an extent, to it. The minor loads of T_m and C_2 are acting in there also. T_m is being stretched without much resistance considering its temperature. The balance is producing a nice and straight weld. Now the arc approaches a place where the gap changes to 0.006 inches in one quarter inch of run. Suddenly the plates are pushed apart almost 0.004 inch, the after-puddle material is abruptly stretched and if it cannot strain gracefully then it cracks between the weakest planes to relieve the tension. Furthermore it seems reasonable, (and as good a suggestion as any) to think that such a tension on the mushy zone could precipitate a tension-relieving-porosity which might not appear otherwise. An array of strain gages parallel to a weld has shown this transverse tension after the puddle as a spike on a record when the arc came to the point on a long tapered gap where the gap changed from opening at the rate of 0.001 inch per inch to closing at 0.001 inch per inch.

Consider how many times the gap changes, so insignificantly from a dimensional point of view, on an edge hand filed for machine welding. These little geometric but large dynamic activities occur on a machine weld when no change is made to any of the machine settings. But look at such a weld. In spite of constant parameters held to within $\pm$ 2% of set values bead face and root width and height variations may vary commonly to 20% of nominal without an apparent reason. In the extreme the following may be found in the vicinity

(1) A crack, porosity;

(2) Bead crown thinout sometimes accompanying overpenetration even burnthru;

(3) Bead crown rise accompanying lack of penetration; and

(4) A crack and porosity.

If they should all appear the conditions would appear one after the other in the order shown counting in the direction of weld travel Why?

(1) The crack and porosity after the puddle occur because the plates are pushed apart by the instant rise in the force of C_1. (like Fig. 7).

(2) The liquid of the puddle is stretched at the same time causing it to drop and have a thinned bottom. This drops the arc and causes overheating.

(3) With 0.500 inch more of arc travel the rigid extraordinary C_1 collapses plastically (as it rises through 600°F). It upsets and the centerband ahead of the puddle thickens The arc then requires up to 15% more current just to maintain a constant root penetration. If current is not increased lack of penetration will occur and the weld crown will rise and narrow.

(4) The last tension occurs because the abnormal upset occurring at the gap closing will, after the puddle passes, turn into an abnormal tensile strain.

The magnitude of the events in this train is increased mainly when the gap rate of change is high, that is when the rise over run is high. For example a 0.004 inch reduction in gap that occurs in 0.200 inch is more serious then 0.010 closure in one inch. It is not 0.004 inch of metal mass to be melted that requires change. It is the instantaneous separating of the parts by that much. The stress events and their visible manifestations are exagerrated when a gap opens, then must close, and when the change is momentary. The rise and fall of anomalous stresses is bad enough when the weld controls are fixed but the problem is compounded and magnified when the operator reacts. The thinout of puddle caused by a closing gap does require a reduction in welding current which an alert welder may provide. But within an inch, when the arc enters the heavy upset, the requirement is extraordinary heat. He usually reacts late to the signs and provides the extra heat when it is not necessary and not wanted.

Optimum Welding Conditions

A quick change in travel, in weld current, in part thickness, in filler metal buildup, in hold-down conditions, or tacks will generate nearly the same train of anomalies. It is interesting to note that these conditions are seemingly so unrelated to one another in kind. So much that those that have been studied have been examined in isolated investigations. But when each is translated into forces exerted around the heat source in combination with the temperature of the material there appears a very important, heretofore unappreciated, common ground or language, one that requires each of those conditions to take into account its effect with the others thru this common channel. Without a fair sensitivity to effect of others on the force-and-stress balance any conclusions about any one's effect on cracks, residual stresses, distortion, even or weld parameters, do not have the general applicability they ought to have, or may seem to have. This is not to say that a conclusion about residual stresses or some other quality for a 10 ipm nominally proportioned weld are invalid. But the reservation is about how generally true the conclusion of such an experiment is. At what rate will the results change if travel speed, bead height, or hold down location change?

Certainly a slowly made weld has stresses formed quite differently from a fast made weld. Even tests of certain locations that appear to be different only in degree between slow and fast are not revealing the sizably different experiences of the micro-structures. Certainly a narrow specimen does not experience the high peak of stresses that a wide specimen does, and it should not carry the same degree of residual stresses in the same fine and critical locations (35% of the stresses in the fast welds may be due to plastic extrusion from longitudinal compression vectors). Surely now, a weld specimen with no butt line gaps must be used only reservedly to predict stresses on a filed field weld.

The sometimes-microcracks and sometimes-porosity have not quite been explained by physical or chemical thermodynamics. Is it at all possible to almost pull porosity out of the solidifying mushy-zone ? This is different then from solidifying castings in which hydrogen pores push their way into being. If that were possible is there a detectable shape or pore size-frequency distribution or a mechanical property difference between two "ex post facto" specimens that at first appear alike but were produced by different routes? Then the conclusions drawn from one should not apply to the other or others.

There is to be found scatter in reported test results, lack of reinforcement by conclusions of different test programs, and so many departures from assumed trends that the <u>different reactions</u> from supposedly standard conditions beg for explanations. One remedy to apply immediately is to specify in all work the value of all conditions especially the heavily instrumental ones discussed here. Test results are often portrayed as "the change of A with a change of B" sometimes with different levels of C, the fact is that the change of A occurs in different degrees for each change in B, C, D, E, etc. Then C, D, E, etc. values must be part of documentation. The entire relationship must look like an n dimensional game of Tic-Tack-Toe. Too frequently other conditions or dimensions (even travel speed) have been thought of as having little influence on A vs B conclusions. Since the nature of the matter is like an "n" dimensional matrix any new information has to be identified by the conclusion and the right address, which is the value of all the relevant conditions. By that, as positions are filled in time a picture will take shape.

Another parallel remedy is to regard dynamic stress and those conditions that can effect it as probably important and set out to measure the effect of change. For example, put a strain gage near a weld. Make a weld and record the change. Change the value of one condition twelve times (like travel speed from 4 ipm to 26 ipm). Then: is the condition significant? If so, one plane in the matrix is defined, i.e. the weight of condition T changes on quality A can be sensibly appreciated or depreciated. By these remedial processes the isolated bits of data may be gradually hung together in the right order.

There are two other regimes, new ones, by which measured coherency may be acquired. The cost of either can be much less in the long run than the early jig saw puzzling suggested by the two prior systems that try to relate isolated experiments.

But first, it is interesting to recognize that a good welder or technician has probably not missed the significance of the important instruments. And his approach is good optimization even without a vision of the subject stress pattern. He will run a weld at one speed, then run one faster. If differences are discernible, and also good he will try a faster speed. If they are bad he will try a lower speed. He will try again and again until he finds one speed that produces better results than the next lower or next higher; or until the results are good enough; or until he has run out of time or money and must use what he has. He may try the same routine with finger hold-down location; and then with the other conditions he has seen to be important. Of course the valuable advantages to be found in reiterating (like doing travel again later) is a level of effort usually omitted. For him an understanding of the stress-characteristic patterns should help emphasize neglected instruments and make optimum hunting a little more rational.

But on a more sophisticated level, it would be more than useful to have an experimental technique or a computer technique that gave a topographic map of stresses or of strains for a given set of conditions. Note that the key qualification in the prior paragraph was the "if discernable". In practice a change of 2 ipm in travel may change the porosity rate from 21 per 1000 inches to 19, but this is hardly observable by a technician or credible in a practical number of laboratory specimens. So if it can be established and agreed that tensile strain on mushy or plastic or firmer aluminum of a given temperature is bad then an effort to create a system to expose the strain at all points on the part for any selected set of conditions would really be priceless.

Here is how a system should be used. Select a set of values for typical welding conditions (travel = 10 ipm, hold-down = 100 pounds per inch at one inch from the weld edge; etc.). Make a weld with this setting observing and recording the strain action. Print a three dimensional plot of strain around the heat source. Change the value of the condition being studied make another weld and draw up another plot. After several changes, the several plots (like the array in Figure 10) can be studied to see if the subject condition has a significant effect on the magnitude and position of the critical strains. And if it does, which value minimizes that strain and which does increase it. Similarly each other notable condition can be changed in order to determine (1) the relevance of the condition to strain and (2) the particular condition value associated with minimum strain. Note that optimum travel speed might be found in 12 welds, finger hold down optimum in 16. The number of welds required to find the optimum set is not large considering the many feet of welding now made to statistically verify small effects.

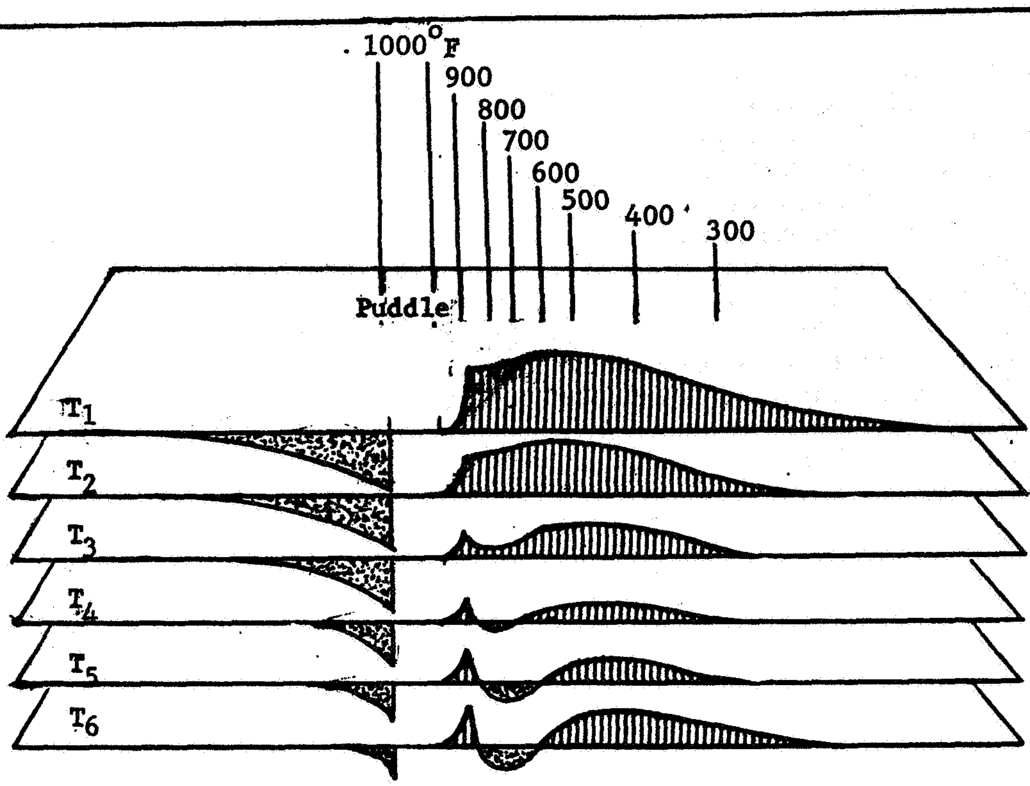

Figure 10 - Here is a simple example of how tensile strain across the centerline might be represented for welds made at six different travel speeds. This is a center section thru the strain map with transverse stretch plotted upward from the no-strain plane. In this, the value of T_4 would probably identify the optimum weld speed. The same kind of array could be made for other significant weld conditions. This kind of information can be quite useful to a metallurgist who is concerned about the strain being suffered by a structure at a given temperature.

Considering the number of welding condition permutations waiting to be examined the measurement-and-observational system should not be the factor to impede progress. To be practical and to let the limit on progress lay with the setup-and-weld repititions the observational system must be almost photographic. With all the welding work to be done hours spent to measure strain in each incremental area of each specimen is inappropriate. Several systems hold potential for "seeing" strain all around a weld. Holography, for example, is one kind of candidate. For those offices whose interest lies in raising the level of industrial science and in making technology felt in the shop it seems that there is hardly a more worthy project than discovering or developing such an observational system. Welders complete millions of tons of work every month in one of the most basic of American industries.

Progress in Welding Science

It seems that past and present research is highly compartmentalized and especially when handled by metallurgists it deals with welds after-the-fact. It is a surprise that the dynamic responses of masses under particular heating, i.e. welding, has received such scant attention. Perhaps shrinkage tensions and residual stresses had seemed to adequately define the regime.

Where should welding science go now? It is proposed, somewhat presumptiously, that the door that must be passed is one that exposes stresses and strains experienced around the weld during welding. Metallographic conclusions and mechanical temperature-strain or stress tests based on assumed experiences by specimen areas, must be called into question until the experience of an increment by a weld can be documented. What really was its stress and strain? Figure 11 provides an example of the pertinence of this question.

Tension is customarily assumed to draw on the solidified bead and the weld-wrought transition structures right from solidification. But this appears to be valid only for the slower welds in aluminum. The faster welds may experience a severe biaxial compressions in the same points after the puddle. Incongruences in the collected body of research on the subject of strengths, fatigue life, ~~and~~ void geometries cannot be dismissed as experimental error. Metallographic and physical tests and organization must relate to the true experiences. Prior assumptions are called into question.

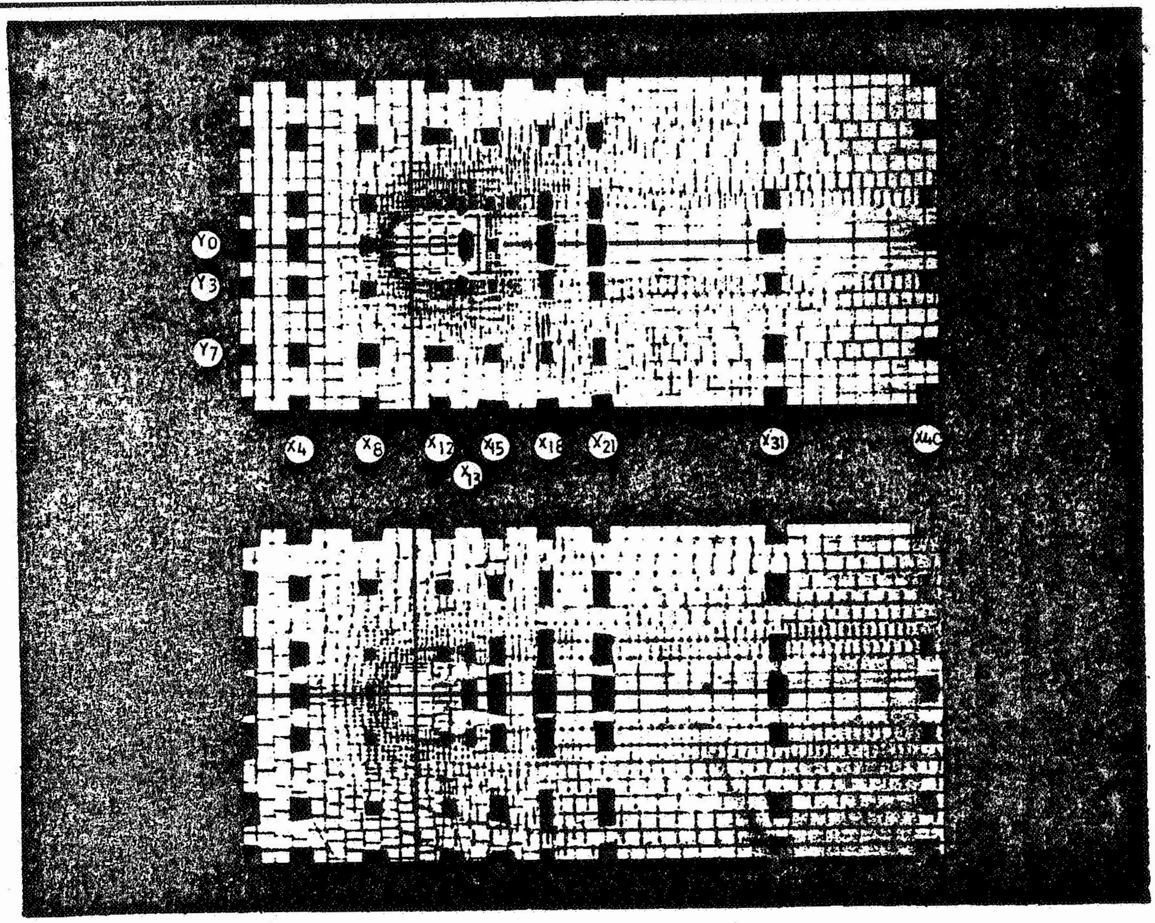

Figure 11 - The experience of a spot on the surface of a weld cannot be safely assumed. Moreso any assumption about the experience cannot be simply transferred to all other welds in the alloy . The gridding here (another possible form of strain expression) represents compression or tension in two axes by shortening or stretching the unit squares. The black tiles symbolize the immediate experience of the increment at the given location. The cast-to-wrought transition zone (lying under Y3) may experience in the fast weld (upper) biaxial compression at X_{15} when it is plastic but a strong transverse tension immediately after when it is short (X_{18}). By contrast the same zone on a slow weld only experiences increasing transverse tension, first on plastic material then on firmer material.

Definition and measurement of actual in opera stresses and strains is a path that must be tread in efforts to further organize independent revelations and make basic researches more pertinent. How else will the great problem of weld parameter optimization be solved? The optimum sought may be the highest strength from an alloy or it can be minimum defects under given conditions. Vaster numbers of permuted and redundant experiments cannot promise the ultimate answers. But just putting an effective system into being should have wide and obvious effects on insights.

About the candidate system: (1) It should be experimental and (2) it should be turned easily into an efficient instrument for answering practical questions. Outside of benefits flowing thru science and a general improved comprehension of events the value of a system to metal fabricators will depend on (1) how much insight it can provide to pattern peaks and shifts for changed conditions in typical alloys and (2) how often it can be called on to solve particular shop problems (which are solved now by craftsmen not scientists).

Of course to be most useful the developed system cannot use a year to make and a year to test one weld. The cost of finding the one right welding parameter for a selected alloy should be low enough to be paid for by the savings to come from the right choice. There are a number of operations valuable enough to pay for answers to those kinds of questions. But the simpler the system is the more problems there are eligible to be economically answered.

Again, the only door to this seems to be welding experiments with an efficient observational system. Solve the problem of exposing strains easily, and energies can be used extracting meaning from graphic data instead of spent pulling data out of parts. This strain portrayal system must be experimental. Certainly the ultimate way to answer a parameter, tooling, alloy, or configuration problem is to punch a set of conditions into a computer with a developed program and letting it draw a map in minutes. Change a condition value and get the next map. But several comments deserve to be made.

First, the experimental mapping system, proven, and trusted must come first. Computer mapping is the door after this. Computer programs are so complicated and require so many assumed boundary conditions that they must be treated with some suspicion until they are verified by a trusted reference system which will have to come by proven experimental system. They must never be used until they produce the same pictures as experimental evidence. Second, some of the formulations or data that are now a fragment of the larger computer program should, and can, be taken from experimentally discovered information rather than pure mathematical roots. The difficult roots may have questionable applicability or be questionable in their complexity. Third, the only practical reason for pursuing a mathematical program is that ultimately the cost-and-time saved in making a valid run on a set of conditions will be less than that of an experimental run. When a strain picture can be drawn in minutes the program work is justified.

If this eventually becomes true then many more applications will be able to afford the cost of optimization: (1) shops may ask frequently for the optimum weld schedule and for application, (2) they may ask for a report on the likely advantage of more expensive tool, (3) a metal company may ask for the reactions of a continuum of alloy variations to a variety of weld conditions and thereby really design a strong and weldable alloy, (4) perhaps ultimately a handbook of strain maps may be printed for each key alloy and used like navigation tables by a technician to determine the best combination of conditions to use to make a given weld. The possibilities are beautiful to consider.

CONCLUSIONS:

The subject of stress and strain fields around a moving heat source is neither too complicated to organize into a coherent visible system nor so simple that residual stresses can be used to describe weld area experiences.

Five stresses act across the weld line in turn as an arc passes. Their proportions and positions are considerably altered by weld parameter or condition changes.

These pushes and pulls effect the metallurgical character and integity of the weld area even when there is no apparent difference between after-the-fact examples.

Comprehension of the stress pattern and its manipulation with shop instruments are easily within the capabilities of the weld technician or welder.

But peak optimization including the greater number of weld conditions awaits an experimental method for "seeing" strains.

Ultimately the computer may be used to replace the experimental system, but it seems it should be only after it has proved (1) equal to the experiment and (2) quicker to execute.

With the completion of each of these stages in turn the advantages to knowledge and to accomplishment will be multiplied, because more questions will be eligible for consideration and solution.

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