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METALLURGY LECTURE SERIES

Lecture II
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INTRODUCTION

This is the second of a series of lectures in physical metallurgy. The first lecture consisted of an introduction to the heat treatment of steel and the age hardening of berrylium copper; with it were presented the allied subjects of phase diagrams and recrystallization. This lecture will deal again with these subjects in a secondary manner as applied to problems encountered in welding.

The American Welding Society defines a weld as "A localized coalescence of metal wherein coalescence is produced by heating to suitable temperatures, with or without the application of pressure, and with or without the use of filler metal. The filler metal either has a melting point approximately the same as the base metals or has a melting point below that of the base metals but above 800° F." This definition encompasses the general fields of Brazing, Flow welding, Resistance welding, Induction welding, Arc welding, Thermit welding, Gas welding, and Forge welding with all their techniques and special problems. The total process of welding involves more sciences and variables than any other in industry; the chemist, the ceramicist, the electrical and electronics engineer, the metallurgist, and the physicist, all could be--and have been--involved in the evolution of welding as a science. Since so many fields of science are involved--heat, mechanics, elasticity, plasticity, electricity, magnetism, physical chemistry--and so on, one is often content with a crude qualitative understanding of welding problems.

In the time available we can only receive another crude picture, and that only if we narrow our sights and merely survey the problems that exist in one small twig on a small branch of the large tree that "welding" presents today. I propose, therefore, to concentrate on the electric arc welding of steel plate as an example from which a discussion period might branch out to more specific questions--as indicated by many of the questions asked in response to the questionaire circulated before this series started.

THE HEAT SOURCE

To start this discussion, let us look first at our source of heat--not too closely--but merely to note our shortcomings in analysis of its part in the production of a sound weld. Though electric arcs have been studied and used for fifty years and more, their properties are complex and studies made upon them require stabilities not yet accomplished in the design and control of industrial welding arcs. Industrial arcs are subject to severe transients and rapid fluctuations of length, current, voltage, and position--characterized, then, by short intervals of equilibrium conditions which may be reproduced for longer periods for study under laboratory conditions, but which, in practice, shift, by transients, to other states which attain equilibrium quickly.

The arc column at about 6000° C Absolute is fairly uniform but is separated by only a few hundredths of an inch from its atmosphere at much lower temperatures. Its temperature is influenced by the actual constituents of the arc which come from its atmosphere, the rod coating materials with their additives for influencing the arc, and the metallic vapors present. Since the electrode and the work cannot greatly exceed their boiling points, the ends of the arc are capped by exceedingly large thermal gradients; the electrode voltage drop regions have been measured as less than .001 mm. The magnitude of these drops varies with polarity, the positive terminal usually being the higher--thus explaining the usual "straight" polarity with the larger mass of the work positive to receive the greater heat.

Actual transfer of metal from rod to work is usually by droplets which complicate analysis since they may short out the arc entirely or divide it into two or more arcs in series, each with its own electrode voltage drop regions.

Aside from the simple function of a heat source, the arc, then, has other functions which must be accomplished--it must strike readily, reignite readily (this requires modification of the power source best adapted to stability); it must transport slag for thermal insulation, oxidation prevention, and maintainence of fluidity of the pool to facilitate gas evolution; and it must generate a gas atmosphere from the rod coating containing the ionizing gases which support the arc, determine its work function and ionizing potentials and supply heat close to the metal surfaces by recombination after dissociation.

This inherent instability should be kept in mind when considering any attempt at quantitative analysis of heat flow in welding.

TEMPERATURE DISTRIBUTION

So now the arc is struck, and welding is proceeding. The operator has selected a rod, adjusted the welding machine for the correct voltage, amperage, polarity, and is attempting to maintain a given rate of travel of the rod along the weld--so many inches per minute. What is the general nature of the temperature distribution in the plates which he is welding.

Again we are faced with a problem that rapidly assumes complications when quantitative analysis is attempted. Along with the uncertainties of how much arc power is actually available to heat the metal, are the others of applying transient phenomena to a three dimensional variable heat flow equation. Convection losses must be accounted for, radiation losses (greater than convection losses only above 500° C.), and Conduction rates which depend on the thermal diffusivity (in turn a function of thermal conductivity, specific heat, and density). Also the factors peculiar to each material enter in--the storage rate for heat (that is its specific heat), the latent heats of transformations (alpha to gamma iron and gamma to delta iron), and the latent heat of fusion. These reversible heats account for about 25% of the transferred heat in the welding of steel.

While this type of analysis may seem cumbersome and too difficult to apply--it has tended to bring into sharper focus the variables involved and explain the "shotgun" curves of earlier work. Also it has enabled investigators to use a minimum of dynamic temperature measuring points to establish whole heat-flow patterns.

Qualitatively, the patterns are like these (Fig. 1 and 2). They show the effects of thickness (Fig. 1), of Nature of Material (Fig. 2 C,D), of current intensity (Fig. 2 A,C), of speed of welding (Fig. 2 A,B), Preheating effects neither their size or shape but will raise the temperature of each isotherm and widen the fusion zone.

MECHANICAL PROBLEMS

The results of such a moving temperature distribution leaving a weld behind explain the mechanical problems of residual stresses remaining and the metallurgical ones of structure of the weld area to bear the mechanical loads.

The Welding Handbook and Lincoln Electric Co's Procedure Handbook give very nice qualitative explanations of residual stress--so I shall follow them--in abbreviated form.

If two triangular pieces of steel 100" long are abbutted to form a trough which can be filled with molten metal at 2800° F. in a short time, we approximate a weld in the most easily analysed case. If the trough is now filled at 2800° F. the whole structure soon reaches a temperature of about 1400° F. or 1500°F. The pour, though now solid, can exert no appreciable force on the trough due to its low yield point. Thus the trough is free to expand and the whole assembly to contract--and if unrestrained at its ends will return to 100" length with no residual stress If restrained at 100" on the ends, upsetting will occur on expansion and plastic flow to about 1% on 1" will shorten the cooled assembly to 99". But again there will be no residual stress since all parts cooled uniformly.

Now let one of these triangular pieces be the beveled edge of a plate. Here the total heat capacity of the molten metal poured in the trough is not sufficient to heat the more remote section of the plate and some portion remains at its 100" length with a temperature gradient and expansion gradient up to the weld area. This case is midway between the two previous cases as far as dimensions go but the end result is a stressed weld and plate. Note also the direction of warpage. During the heating the trough will expand more than the plate and hence will be bowed away or concave to the plate--and after upsetting and cooling will be shorter than the plate and be bowed to or convex to the plate.

If both sides of the trough are the beveled edges of plates and the trough filled as before, there will be upsetting of the trough and weld metal and on cooling, from about 1400 - 1500° F. down, the trough and weld will be pulled in tension while the plate adjacent to it is in compression.

An idea of the magnitude of these stresses may be gotten from (Fig. 2). Here is plotted the % strain due to expansion and elastic limit in mild steel. At any temperature above Tk or 340° F. there is plastic flow induced in cooling of our two plates.

For some temperature above Tk, Say M, there will be an elastic strain of MN' and plastic strain of NN'. If NN' is smaller than OE, the room temperature elastic strain, the residual stress will be below the elastic limit; if greater than OE there will be more plastic flow in cooling and a residual stress about equal to the elastic limit.

In actual welding we have seen from the temperature distribution that the conditions assumed here for the filling of a trough with molten metal are over simplified but help in visualizing the process. With a temperature distribution as we have seen, there is a moving area of expansion and an increasing area of contraction behind it. The relative size of these two areas determines a force on the unwelded seam before the arc tending to close the gap between plates or open it--a small expanding area closing the gap, a large expanding area tending to open it. In either case the residual stress pattern parallel to the weld is as in our trough example, i.e. tension in weld bead and flow area, compression in parent metal.

METALLURGICAL ASPECTS

Now that the weld has been made examination of its structure coupled with application of many performance tests of the weld structure will reveal in detail the quality or worth of the weld. There are many mechanical tests which have been devised to test the effect of welding variables or groups of variables--some more sensitive to this or that variation in technique in welding--and all in dispute as to their worth in evaluating the property of "weldability".

Microscopic examination seems a more revealing test of a weld in understanding what has taken place so I shall concentrate on this method.

The weld reveals three main zones aside from the base or parent metal there is the fusion zone, the grain coarsening range and the grain refining range. In the fusion zone of the weld, the structure is that of a casting, its grains are large and elongated in the direction of their growth from the rim of the pool to its center. Often chemical segregation of alloying elements of the weld metal is in evidence and the grains are cored--that is, made up of layers of metal of differing composition. Like a casting it may show porosity due to gassing as the molten metal cools and it may show flux inclusions as in a casting. It is usually through the fusion zone that cracks propagate most readily for the cast structure is least adapted to flow plastically in a uniform manner as is a wrought plate.

The grain coarsening range is that section of metal which was raised to temperatures between the upper critical, A_3 (1333 to 1670° F. depending upon carbon content) and the melting point at about 2800° F. In this section the carbides dissolved in the transformed ferrite to form austenite with fine small grains at A_3, the grains growing in the further heating from A_3 to higher temperatures. In the rapid cooling which follows, the transformation back to ferrite and carbides may be at grain boundaries (the high temperature austenite grain boundaries) or along planes of those grains. This section, then, has a coarse structure with a non-homogeneous distribution of carbon contents.

The next area discernable is the fine grained area which attained temperatures within the A_1 - A_3 temperature zone (1333 to 1670° F.). Here transformations were not complete and growth of austenite did not take place.

All parts of the plate further from the weld than this did not change in structure as the weld passed and were practically unaffected--except for a slight annealing next to the refined area.

If the weld metal or plate should be of sufficient hardenability so that in being heated through these ranges of temperature and cooled, the critical cooling rates are exceeded--a portion or all of the structure in that area might be quenched to martensite just as in the heat treating of that type of steel, its hardening response is determined by temperature and quenching rate.

The structure then is a key to what has happened in the weld zone--knowing the composition and hardenability of the plate, much can be learned of temperature distributions and cooling rates in the welding process.