Selection of Processes for Welding Steel Rails

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ABSTRACT

The advantages and limitations of several conventional and prospective rail welding processes are reviewed with emphasis on the heat input rate, on joint preparation, on post weld grinding and on resultant metallurgical structure. Particular attention is given to thermit, flash and oxyacetylene processes with some discussion of the potential of resistance butt, electroslag, laser and electron beam processes. Simple models of the processes are presented to aid in understanding the limiting parameters for each process. It is concluded that there is little chance of increasing the speed of existing oxyacetylene and flash processes due to heat transport limitations, nor would such changes be desirable from a metallurgical point of view.

INTRODUCTION

In recent years there has been a tremendous demand for economical, productive and reliable techniques for welding of steel rail. The traditional processes of thermit, oxacetylene and flash welding are well proven and generally exhibit a low rate of repair when properly controlled. Nonetheless, there is increasing interest in newer technologies such as laser, electron beam or homopolar pulse and in application of older techniques such as electroslag.

In the present paper, these processes are reviewed briefly in terms of their heat input characteristics. It will be shown that this approach allows one to estimate the thermal cycles for each process and to infer certain advantages and disadvantages for each process based on classification by heat input rate.

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CLASSIFICATION OF WELDING PROCESSES

There have been many attempts to classify welding processes (4-6), and each has its own strengths; however, a rational approach to classification has to address the resultant parameter of interest. For welding of high carbon steels, such as rails, the critical cooling rate between 800 and 500°C is of great importance since this parameter controls final weld microstructure and strength. Accordingly, it seems appropriate to classify welding processes for rail by the thermal history.

There are two types of heating which may be applied to a metal, viz. superficial and volumetric. Surface heating occurs when the outer portion of the metal is brought to an elevated temperature, and the heat diffuses into the bulk of the metal. Thermit, electroslag, flash, oxyacetylene, arc, laser and electron beam processes produce surface heating. In these cases, the interior of the metal is controlled by the thermal diffusivity, \( a \). Dimensionally, it can be shown that the thermal diffusivity is related to the distance, \( x \), that heat travels from the surface in a time, \( t \), by

\[
a \sim \frac{x^2}{t}
\]

Since \( a \) for steel is approximately 0.1 cm\(^2\)/sec, a steel bar heated on its surface will be heated to a depth of 0.3 cm (\( \frac{1}{4} \) inch) in one second, 1.0 cm (\( \frac{1}{2} \) inch) in ten seconds, 3.0 cm (\( \frac{1}{2} \) inch) in 100 seconds and so forth.

There are very few physical processes which produce volumetric heat generation in metals. Two examples are induction and electrical resistance, both of which generate heat by exciting the electrons in the metal. Nonetheless, these processes are also limited by the diffusion of the magnetic and electrical fields into the sample. While this magnetic diffusivity is much faster than the thermal diffusivity of the steel, too high a frequency of inductive power or two short a pulse of resistive current will result in a "skin effect" which approximates surface heating. Generally for steel rails, the optimum induction frequency is around 1 to 10 kHz, hence, the skin effect is only important for welds made in less than one millisecond, which currently is not a practical limitation.

There is no common process which achieves volumetric cooling, hence, the cooling rate of a weld or any hot body of metal is controlled by the same basic parameters listed in Equation (1).

Given this background, it can be seen that the heating and cooling of most rail welding processes is controlled by the surface heating process. Figure 1 represents a classification of processes by the rate of surface heat input (i.e. surface power density). There are a number of advantages to using this classification. One is that the time to complete the weld is inversely related to the input power density. This is due to the fact that it requires a fixed amount of energy to raise steel to (or near) its melting temperature. If this energy is absorbed very
quickly, i.e., high power densities, the time to produce the weld is reduced proportionally.

The general time relationship of Figure 1 also illustrates another feature of this classification: as the time for completion of the weld decreases at high power densities, the need for automatic control increases. As an example of this, the low power density thermit process is often controlled by manually determining the time of crucible tapping; whereas no one would consider manually timing a higher power density laser or electron beam welding machine. In this latter case, the weld pool is produced in a few milliseconds and no human operator can respond at this speed.

These last factors illustrate still more features of this classification scheme. Automatic controls generally result in higher costs for capital equipment. The equipment for thermit or electroslag welding is inexpensive; but homopolar, electron beam and laser equipment can be very expensive depending on how well automated it is made. In addition, it is often the case that the higher power density processes have narrower tolerances for error. For example, the root gap of a thick section laser or electron beam weld must usually be 0.5 mm (0.020 inch) or less, thus requiring machined end surfaces. In contrast, a thermit or electroslag weld can tolerate gaps between 1.5 cm and 3 cm (½ to 1½ inches).

These limitations of high power density processes are not rigid. For example, it is possible to defocus a laser beam to a lower power density and thus achieve more tolerance for deviations in joint fit-up, however, one has to determine if the characteristics of the defocused heat source justify the more expensive process. After all, a laser defocused to 10,000 watts/cm² is competing with the cost of a much less expensive arc welding machine! The most expensive high power density processes do have the advantage of being capable of simulating low density processes, whereas there is no method of extending thermit or arc processes to the power densities obtainable by laser and electron beam.

SIMPLIFIED MODEL OF HEATING AND COOLING OF WELDS

In order to illustrate the heating and cooling cycles produced by different
surface power densities, two known solutions to the solid heat conduction equation were used.

The solution for a semi-infinite, one-dimensional body heated on its surface is given by:

$$ T - T_o = \frac{q}{\rho c} \left( \frac{t}{\pi a} \right)^{1/2} e^{-x^2/4at} - \frac{qX}{2a} \operatorname{erfc} \frac{x}{\sqrt{4at}} \tag{2} $$

where
- $T$ is temperature
- $T_o$ is room temperature
- $q$ is heat input density
- $\rho$ is density
- $c$ is specific heat
- $t$ is heating time
- $x$ is the distance from the joint
- $a$ is thermal diffusivity

The solution for cooling of the same type of body with an arbitrary initial temperature gradient is given by:

$$ T = T_o + \frac{2}{\ell} \sum_{n=0}^{\infty} \exp\left(-\frac{(2n+1)^2 \pi^2 t}{4 \ell^2}\right) \cos\left(\frac{(2n+1)\pi x}{2\ell}\right). \tag{3} $$

$$ \frac{2\ell(-1)^{n+1}}{(2n+1)\pi} \left[ f(x') \cos\left(\frac{(2n+1)\pi x'}{2\ell}\right) \right]_0^\ell $$

where $f(x')$ is the initial temperature distribution in the solid $\ell$ is the length of the body, which in this case is defined as a very large value with respect to $x$ and $t$ as given in Equation 1.

These two equations were programmed into a minicomputer and solved. The time of heating (Equation 2) was adjusted to bring a steel sample above or close to the melting point. The sample was then allowed to cool by simple conduction as described by Equation (3). Figure 2 gives some of the results of this analysis for surface heat inputs increasing from 400 to 8,000 watts/cm$^2$ and heat times decreasing from 120 seconds to one second. It is seen that these parameters span the range of conventional rail welding processes in addition to arc welding. The natural consequences of Equation (1) in limiting the penetration of heat into the base metal at successively shorter heating times is evident. In an arc weld, at 3,000 watts/cm$^2$ for four seconds, the heat affected zone is less than a centimeter wide. In a thermit weld, preheated with an oxyacetylene flame for over two minutes, the heat necessary to cause transformation of the steel to austenite has travelled over three centimeters. While the numbers given in Figure 2 are only approximate for a given welding process, the trends are apparent.
FIGURE 2. Temperature profiles produced at the end of heating for five different input power densities. The surface heat inputs increase from 400 watts/cm² to 8,000 watts/cm² and the heat time decreases from 120 seconds to 1 second. A longer heating time is required to raise the surface temperature to the melting point at lower power densities and thus results in a flatter temperature distribution.

Figures 3a, b, and c give the cooling rates corresponding to the heat inputs of Figure 2 at locations of 0.1, 1.0, and 3.0 cm into the steel. In Figure 3c in particular, it is seen that the maximum temperature in the heat affected zone is often not reached until a number of seconds after the end of heating. This movement of the maximum heat location with time greatly complicates the analysis of residual stresses produced during welding; however, with the aid of the computer, today this problem can readily be solved.

Since the cooling time between 800 to 500°C is crucial in determining the microstructure of the steel, Figure 4 is presented to summarize the effect of
FIGURE 3a. Calculated cooling rates at a distance of 0.1 cm from the heated surface for the five heat cycles specified in Figure 2. Lower power densities produce more effective "preheating" and result in slower cooling.

The eutectoid carbon steel rails require approximately 20 seconds to avoid transformation to martensite.* It is seen in Figure 4 that the conventional thermit, flash and oxacetylene processes readily achieve these slow cooling rates, although thermit and flash would not achieve these rates without the three to four minute preheat that is commonly used. The one percent chromium rails can require cooling times from 800 to 500°C of 500 to 1,000 seconds; and hence, these steels will require longer preheats to prevent bainitic and martensitic struc-

*It should be noted here that flash and thermit processes can potentially approach the heat input rates of welding arcs, but both processes are usually retarded somewhat to produce lower than their maximum power densities.
FIGURE 3b. The cooling rates produced 1.0 cm from the heated surface.

Finally, it is useful to compare these predictions with actual results from thermit welds. Fortunately, Schroeder and Poirier\textsuperscript{12} have recently made some measurements which can be used to check the analysis of heat inputs presented here. Figure 5 gives the predicted heating profiles for two heating times along with the experimental results of Schroeder. The experimental values are higher at long distances from the surface and are lower than the predicted values near the surface. This is due to the fact that the heat transfer efficiency of the flame is greater at early times on cool surfaces and is less on hot surfaces. The average power density is approximately 400 watts/cm\textsuperscript{2}, although it is greater than this at early times and less than this at later times. From this comparison, we may
RAILROAD RAIL WELDING

COOLING RATE AT 3.0CM

\[ q = 400\text{W/cm}^2, 120\text{sec heat} \]
\[ q = 600\text{W/cm}^2, 35\text{sec heat} \]
\[ q = 1600\text{W/cm}^2, 10\text{sec heat} \]
\[ q = 8000\text{W/cm}^2, 4\text{sec heat} \]
\[ q = 8000\text{W/cm}^2, 1\text{sec heat} \]

FIGURE 3c. The cooling rates produced 3.0 cm from the heated surface.

Referring back to Figures 2 and 4, it can be seen that high power density processes will require extensive preheat if martensitic heat affected zone structures are to be avoided. Figure 2 can be used to estimate the width of the heat af-

estimate that Schroeder's flame gave a power density of more than 400 watts/cm² for the first minute or so of heating and a power density of less than this later in the cycle.

Figure 6 shows the cooling curves for this same hypothetical 400 watts/cm², 120 second weld compared with Schroeder's experiment. Again, the approximate analysis gives reasonable agreement. Figure 7 compares the theoretical and experimental results for Schroeder's long preheat weld. The agreement could be improved through refinements in the model. Nonetheless, the model as it stands can be used to predict the weldability of new steels or the applicability of new processes for welding of steel rail.
fected zone, while Figure 4, or adaptations thereof from Equations 2 and 3, can be used to predict the required preheat temperatures. It can readily be seen that the more rapid heat input processes such as arc, laser and electron beam, lose some of their productivity advantage by requiring preheat times as long as the more conventional processes. Due to this limitation that cooling rates should be slow to prevent metallurgical damage, and the fact that the material property of thermal diffusivity controls bulk surface heating and cooling (cf. Equation 1), it is unlikely that welding of rail can be reduced from four to five minutes heating time as currently used. For alloy rail the required heating and cooling times can be substantially longer. The possibility of using volumetric heat generation processes, such as induction or homopolar resistance, offer some
interesting possibilities of overcoming this surface heat power limitation, especially for alloy rails.

There are several advantages of high power density processes. One is the generally smaller weld pool size, which will usually produce less excess metal and hence can reduce grinding. As a result, one cannot look at these processes solely from the aspect of weld time, but one must consider the total preparation time, weld time and finishing time cycle in order to choose the best process. Figure 8 attempts to summarize several of the factors necessary to consider when selecting a welding process.

FIGURE 5. Temperature distributions in the steel at the end of preheating for two and three minutes time. The circles represent Schroeder's experimental data, and the lines are predictions of the model presented in this paper.
FIGURE 6. The peak temperature distribution resulting from a 400 watt/cm² heat input of 120 seconds duration. The highest temperature reached at any location for any time gives the peak temperature distribution. This is compared with the experimental data of Schroeder. The variations in the experimental data are due to measurements made at different positions in the head, web and base of the rail.

MORE COMPLEX MODELS

A very simple model, the solution of which has been available for some time, has been presented and applied to selection of rail welding processes. Much more complex models of varying factors of concern in rail welding are available; however, the assumptions of these more complex models cannot be applied directly to rail welding without significant revision and in some cases, more experimental input. Models of residual stresses, segregation during casting,
The peak temperature distribution resulting from a 400 watts/cm² heat input of 180 seconds. The peak temperatures calculated by the model are compared with Schroeder's experimental results.

FIGURE 7. The peak temperature distribution resulting from a 400 watts/cm² heat input of 180 seconds. The peak temperatures calculated by the model are compared with Schroeder's experimental results.

electroslag welding, and slag-metal reactions are available and represent significant scientific knowledge that can be applied to welding of steel rails. In many cases, these models can provide significant conclusions that are not possible to obtain readily by experiment. These conclusions can often be used to improve the welding process.

CONCLUSIONS

A method of classifying rail welding processes by input power density has been presented which allows a general prediction of welding times, cooling rates,
### SELECTION OF PROCESSES FOR WELDING STEEL RAILS

<table>
<thead>
<tr>
<th>Welding Process</th>
<th>Heating Power Density, W/cm²</th>
<th>Heating Time, Sec.</th>
<th>800 to 500°C Cooling Time Without Pre-Heat</th>
<th>Preheat Required to Prevent Cooling from 800 to 500°C in less than 20 sec, °C</th>
<th>Cost of Equipment</th>
<th>Weld Preparation Time</th>
<th>Amount of Post Weld Grinding</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermite</td>
<td>400</td>
<td>200</td>
<td>200</td>
<td>none</td>
<td>very low</td>
<td>short to moderate</td>
<td>large</td>
</tr>
<tr>
<td>Oxyacetylene</td>
<td>400</td>
<td>200</td>
<td>200</td>
<td>none</td>
<td>low</td>
<td>short</td>
<td>large</td>
</tr>
<tr>
<td>Flash Butt</td>
<td>600</td>
<td>150</td>
<td>100</td>
<td>none</td>
<td>moderate to high</td>
<td>short</td>
<td>large</td>
</tr>
<tr>
<td>Electroslag</td>
<td>200</td>
<td>600-1,000</td>
<td>&lt;400</td>
<td>none</td>
<td>low</td>
<td>short to moderate</td>
<td>large</td>
</tr>
<tr>
<td>Arc</td>
<td>3,000</td>
<td>10</td>
<td>&lt;30</td>
<td>200-300</td>
<td>low to moderate</td>
<td>short to moderate</td>
<td>moderate</td>
</tr>
<tr>
<td>Homopolar</td>
<td>100,000</td>
<td>1</td>
<td>&lt;5*</td>
<td>/</td>
<td>high</td>
<td>moderate to long</td>
<td>large to moderate</td>
</tr>
<tr>
<td>Electron Beam</td>
<td>1,000,000</td>
<td>0.2</td>
<td>&lt;1*</td>
<td>500</td>
<td>very high</td>
<td>long</td>
<td>small</td>
</tr>
<tr>
<td>Laser</td>
<td>1,000,000</td>
<td>0.2</td>
<td>&lt;1*</td>
<td>500</td>
<td>very high</td>
<td>long</td>
<td>small</td>
</tr>
</tbody>
</table>

* At these very short times the simple analysis given here begins to become incomplete.

* Volumetric heating may provide adequate "preheat".

**FIGURE 8.** Estimated values of parameters which may be useful in selecting a rail welding process.
preheat requirements and the like for a number of welding processes. A simple solid heat conduction model has been used to confirm the usefulness of the classification. It is felt that in many cases this simple model is all that is needed to predict general welding process parameters. In more complex situations where convection in liquids, chemical reactions or thermomechanical stresses are involved, more complex models are generally available and could be applied to welding of steel rails to provide new insights and better control of the process.

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REFERENCES

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