Heat Transfer Modelling in Wide Gap Rail Thermite Welding

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ABSTRACT

In the current study, a thermal model was used to investigate the effects of welding parameters on the distribution of temperature in wide gap aluminothermic rail welds. To solve the governing thermal equation, SUTCAST, a finite difference program (FDM) was employed while different aspects such as phase change and convective heat transfer in weld pool were taken into account in the numerical solution. To validate the predictions, the modeling results were compared with the experiments and despite some utilized simplifications, a reasonable agreement was found between numerical and experimental results. The effects of welding variables such as preheating; initial liquid temperature and weld gap on temperature distribution were studied. The results of the modeling showed that the magnitude of weld gap had the greatest influence on thermal behavior of the joint and the highest weld gap results in most stable results.

1. Introduction

Thermite welding is a process in which heat released from aluminothermic reaction is used for melting large industrial components [1,2]. Effortlessness, cost-effective and ease of transportation are the main reasons for the extensive use of the process for welding and repairing the rails in railway industries [3,4]. Weld gap is one of the most important factors affecting the weld properties, so thermite welding is divided into three groups based on the gap size. In narrow gap and wide gap thermite welds, the gap size is smaller than 1inch and greater than 3 inches, respectively and the gap between 1 to 3 inches is named medium gap size. Repairing the faulty rail can be done by cutting defective section, using a rail segment with a 4.5 to 6 m length and employing two narrow gap size welds. Although this operation can eliminate one defect but creates two intrinsic imperfections which will be active at certain conditions in future. Use of one wide gap weld instead of two narrow gap welds is another solution which can decrease the number of welds in railroads and cause saving in time and cost so a decrease in cost about 900$ per each weld can be attainable [5].
Similar to all fusion welding processes, final quality of thermite welds depends on thermal conditions introduced during welding operation.

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Macro and micro-structures, welding defects and residual stresses are some of the welding-related events affected by weldment thermal history. In spite of thermal cycle importance, a few investigations have been carried out on heat transfer analysis of thermite welded structures. Schroeder [6] and Jha[7] studied thermal distribution in base rails and heat treatment after welding but ignored to study the thermal conditions in weld metal and in base rail immediately adjacent to weld metal. Chen *et al*. [8] have simulated heat transfer in narrow gap size thermite welds by a finite-element method using FIDAP package from fluent but disregarded studying thermal conditions appeared in wide gap thermite welds regardless of thermal variations which occur when gap size range changes. They included heat conduction in modeling explicitly and took into the account other thermally physical phenomena such as solidification, melting, heat conduction and radiation through material properties, initial and boundary conditions. They also employed uneasily measurable preheating heat-flux to describe preheating conditions obtained in parent rail while this could be performed with temperature as a measurable parameter. Their results show that gap size is the most important parameter that influences the thermal behavior of narrow gap welds and welds with greater gap size exhibit low sensitivity to variation of other parameters, so that stable thermal conditions can be attained in welds with greater gap size. According to the authors' research, no comprehensive study has been conducted in wide-gap thermite rail welds.

In this study, heat transfer and thermal distribution in wide gap thermite rail welds and the effects of initial melt temperature, preheating temperature and gap size are investigated. Furthermore, preheating operation was taken into the account through measurable preheating temperature which is more applicable than preheating heat-flux used by Chen.

2. Model development

Figs. 1 and 2 show different parts of physical model used for wide gap thermite rail welds. The external segment of model including two halves of silica form mould and the welded rails are seen in Fig. 1 and the rails with the molten filler metal are shown in Fig. 2. The dimensions of the mould is 381 mm×153 mm ×138 mm.

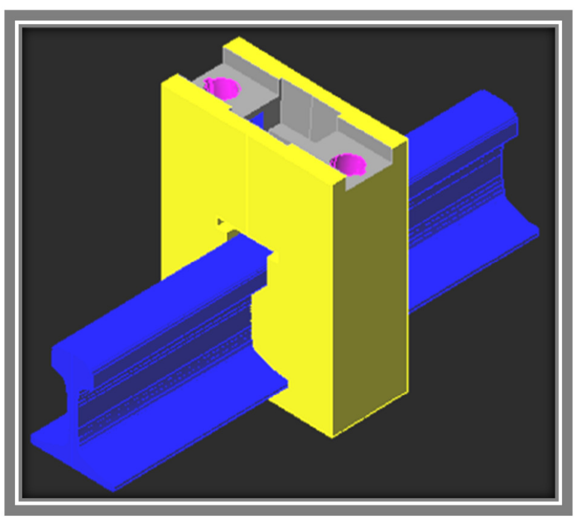


Fig.1. Physical model including two halves of form mould and rails.

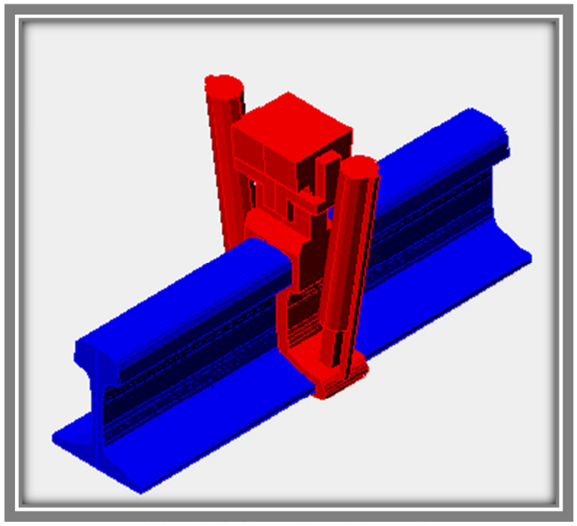


Fig. 2. Rails and weld metal.

The model is symmetric on the longitudinal plane, so one half of the model was meshed and studied. A heat transfer model was introduced to analyze thermal behavior of this process using SUTCAST, the finite-difference package from Razi Metallurgical Research Center. This software has originally been developed to simulate heat transfer and fluid flow in casting parts. It is necessary to delete the previously defined air gap at rail-melt interface, to allow melt penetration and hence the occurrence of welding. It can happen if a high heat convection coefficient is applied at the rail-melt interface. Because of intricate character of the process, it is difficult to incorporate all the involving parameters in the model. According to Chen's study, conduction as prevailing heat transfer method was explicitly considered in the model as follows:

$$\nabla(k\nabla T) + Q^{\circ} = \rho Cp\frac{\partial T}{\partial t} \quad (1)$$

Where *k* is the thermal conductivity, *T* the temperature in Kelvin,Q^o the heat generation rate, *p* the density, C_p the specific heat and*t* the time. From the other thermally physical process, heat convection was included through material properties and radiation was ignored.

A convection type heat transfer was applied by the boundary condition summarized in Table 1 and illustrated in Fig. 3 along with the initial and boundary conditions shown in the same Fig. The (0, 0, 0) was selected as reference point and a mesh with 2 mm length in all directions was chosen for one half of the physical model. Tables 2 and 3 show the chemical compositions of steel rail and weld metal, respectively.Weld metal has relatively the same composition as steel rail does, so the same thermal properties were selected for both of them. Fig.4 shows variation of thermal conductivity and specific heat as a function of temperature, respectively.

Table 1. Boundary conditions

Boundary zone	back	Front	Right	Left	Bottom	Top
Environment type	Convection	Insulation	Convection	Convection	Convection	Convection

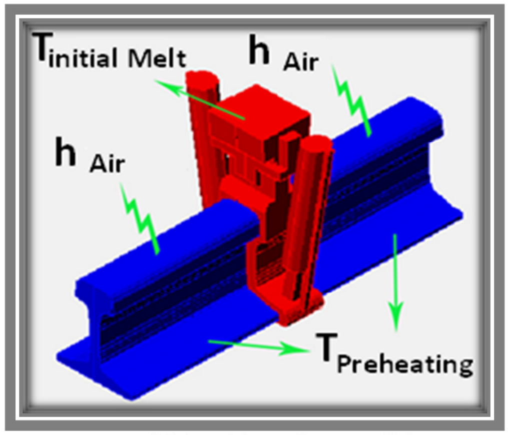


Fig. 3. Initial and boundary condition.

Table 2. Chemical composition of steel rail (wt%)

C	Si	Mn	P	S	Fe
0.554	0.240	0.880	0.016	0.024	Bulk

Table 3. Chemical composition of weld metal (wt%)

C	Si	Mn	P	S	Fe
0.577	0.44	0.600	0.012	0.011	Bulk

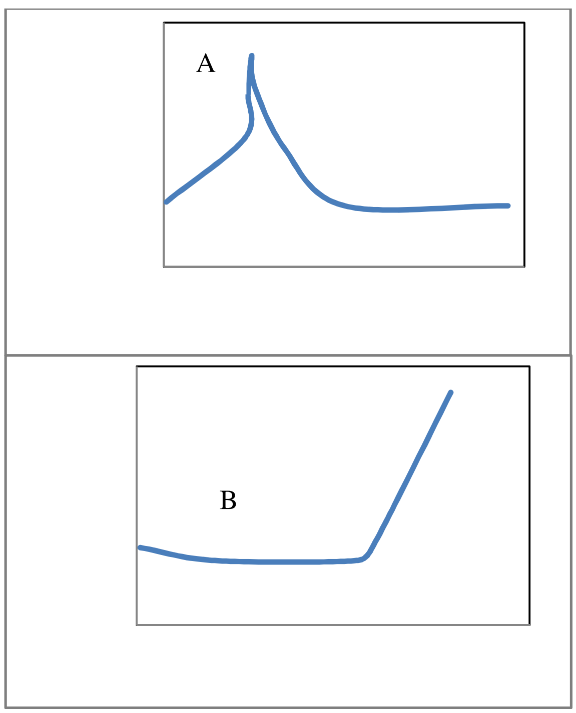


Fig. 4. Thermal conductivity and specific heat of rail and weld metal as a founction of temperature.

High heat transfer by convection in molten metal at temperatures above melting point was taken into account by applying a factor of 3 in thermal conductivity of steel rail. Latent heat generated or absorbed during solid-state transformations and melting or solidification phenomena were also included through the specific heat term in equation 1.

3. Validation

In order to validate the developed model, two segment rails with standard specification UIC60-Grade700A, and composition tabulated in Table2 and welding conditions listed in Table 4 were joined together with molten metal from reaction of thermite powder in a silica mould enclosing the rails as shown in Fig. 2. The thermal result of sample S5 was used for verification of thermal model.The prepared joint was cut and sectioned longitudinaly and then, macroetched with 17% HCl solution in molten state for 30 min. Penetration depth observed in experimental specimen was compared with simulation result. The simulation result was in good agreement with experiment. Further details are mentioned in the next section. After validation, in order to investigate the effects of initial liquid temperature, weld gap and preheating temperature, welding conditions given by Table 5 were designed and the results are discussed in the following section.

Table 4. Experimental welding variables

variable	Weld gap (mm)	Preheating temperature (^{o}C)	Initial liquid temperature (^{o}C)
Value	70	850	2250

Table 5. Welding conditions used in simulation

Sample	Weld gap (mm)	Preheating temperature(^{o}C)	Initial liquid temperature (^{o}C)
S_1	60	850	1850
S_2	60	850	2050
S_3	60	850	2250
S_4	50	850	2250
S_5	70	850	2250
S_6	60	350	2250
S_7	60	600	2250

4. Results and discussion

Fig. 5 compares the amount of melt penetration obtained from experimental measurement with simulation result at S_5 condition. Despite the assumed simplifications, only 0.17% difference existed and hence, there was a good agreement. Temperature variations at S_1 condition and in two different time ranges are shown in Fig. 6. As can be seen, the temperature was first raised from rail corner to rail center and then, was decreased from center to corner. Fig. 7 shows the effect of melt temperature on temperature distribution at S_1, S_2 and S_3 specimens. As can be seen, in addition to melt penetration, the temperature of all points in rail head, web and base increased with the increase in melt temperature. This was an expected phenomenon, because of the increasing heat input with increasing melt temperature.

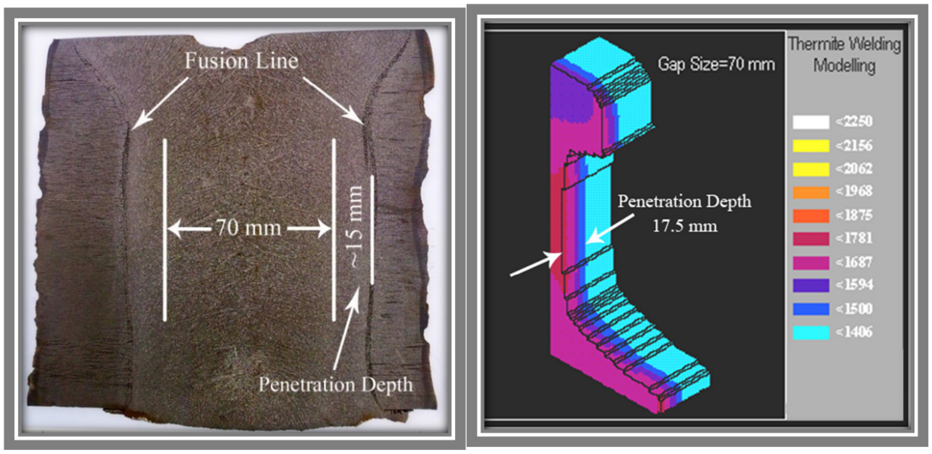
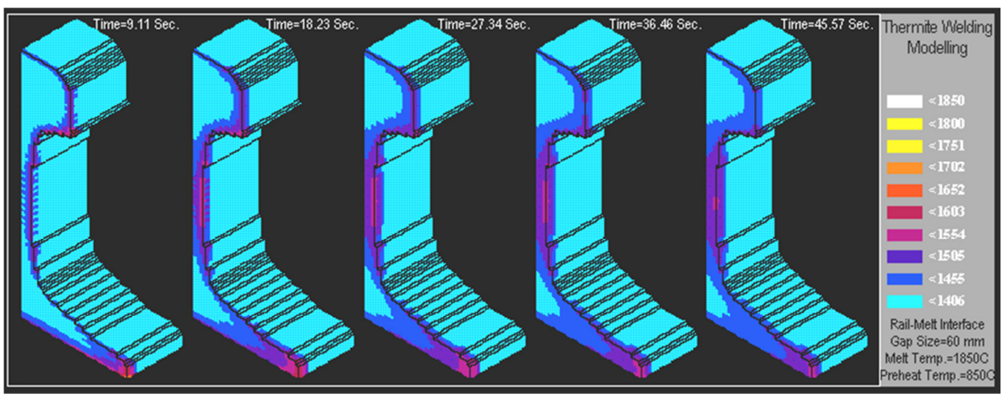
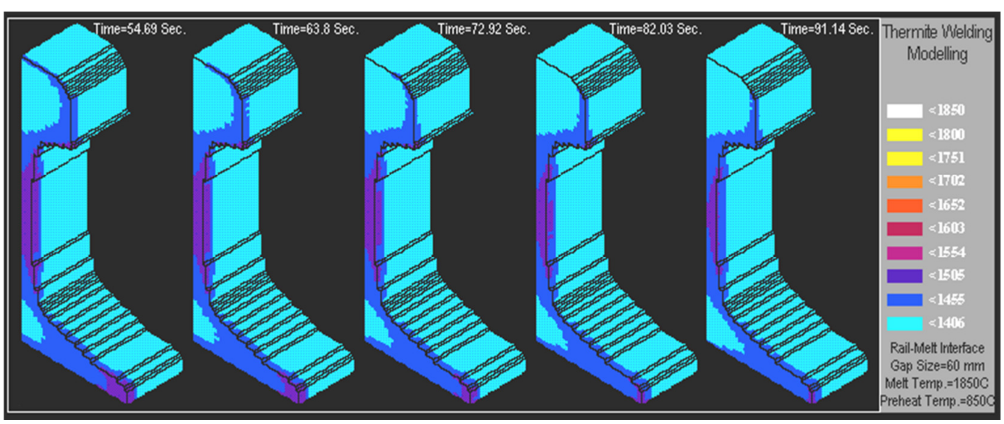


Fig. 5. Comparison between amounts of melt penetration obtained from the experimental measurement with the simulation result at S_5 condition.



(a)



(b)

Fig. 6. Isothermal profile at S_1 condition: (a) Time 9.11 sec.-45.57 sec(b) Time: 54.69sec.-91.14 sec.

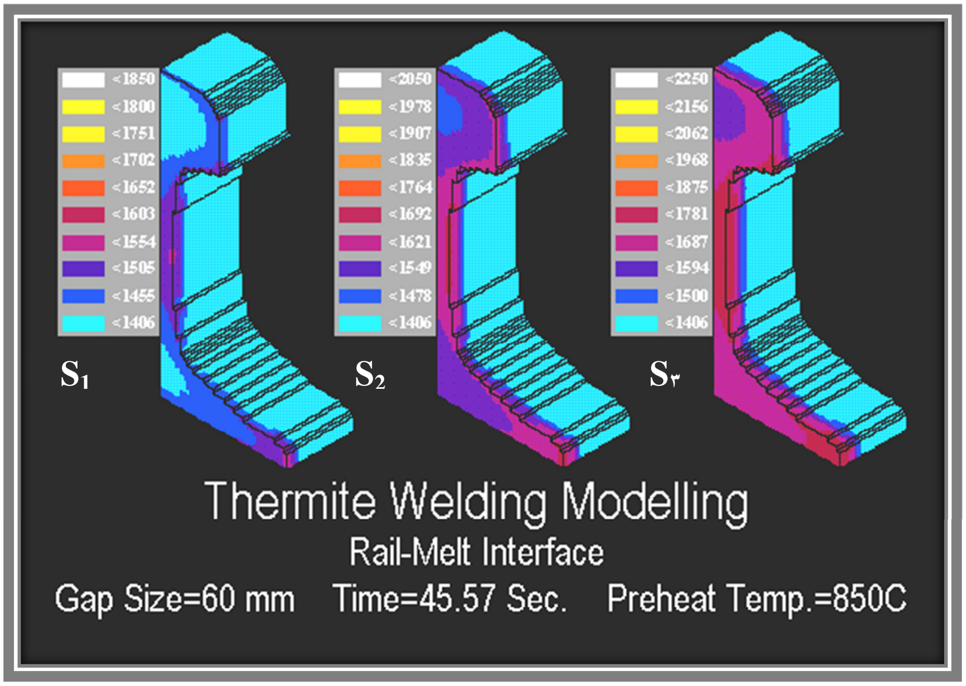


Fig. 7. Effect of initial melt temperature on melt penetration.

The effect of weld gap on melt penetration is shown in Fig. 8. The extent of high temperature areas increased with the increase in weld volume as well as the increase in maximum temperature of rail points, with increasing weld gap. The amount of heat input has increased with the increase in weld volume, as expected.

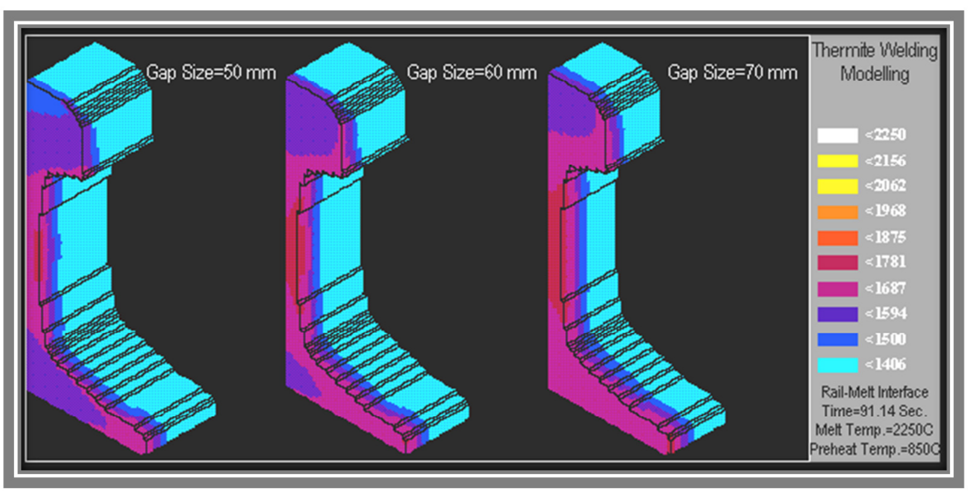


Fig. 8. Effect of gap size on melt penetration.

The preheating temperature is another parameter which can affect the rail temperature distribution. Fig. 9 shows the effect of preheating temperature on melt penetration.The larger preheating temperature causes the greater extent of melt penetration. Heat sink which is introduced by rail bulk caused temperature of rail points to increase in addition to melt penetration. Fig. 10 briefly shows the effect of the discussed parameters on melt penetration. As can be seen, the effect of weld gap on weld penetration was greater than the others. This is in agreement with Chen's results. So, if weld metal is established with maximum possible weld gap, the effect of other parameters will be negligible. In this situation, the results will be less sensitive to the variation of other factors and stable weld penetration can be obtained.

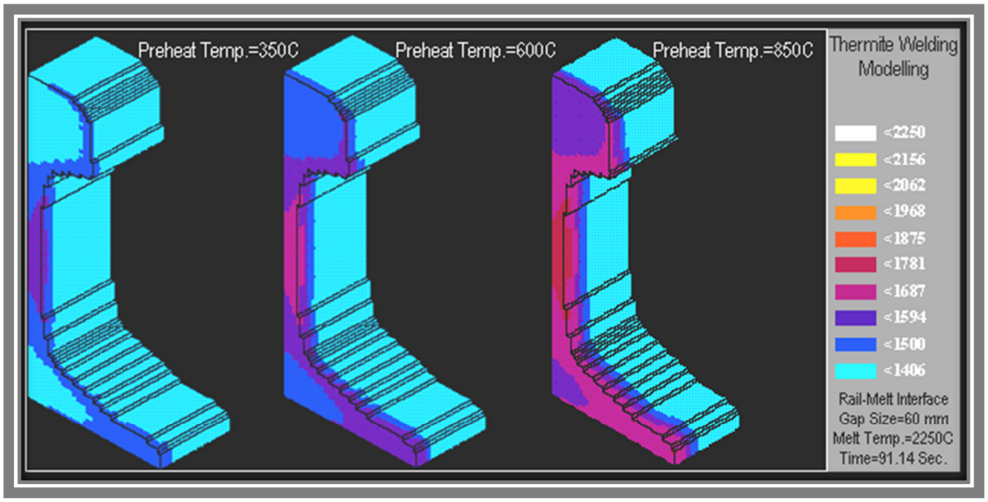


Fig. 9. Effect of preheating temperature on melt penetration

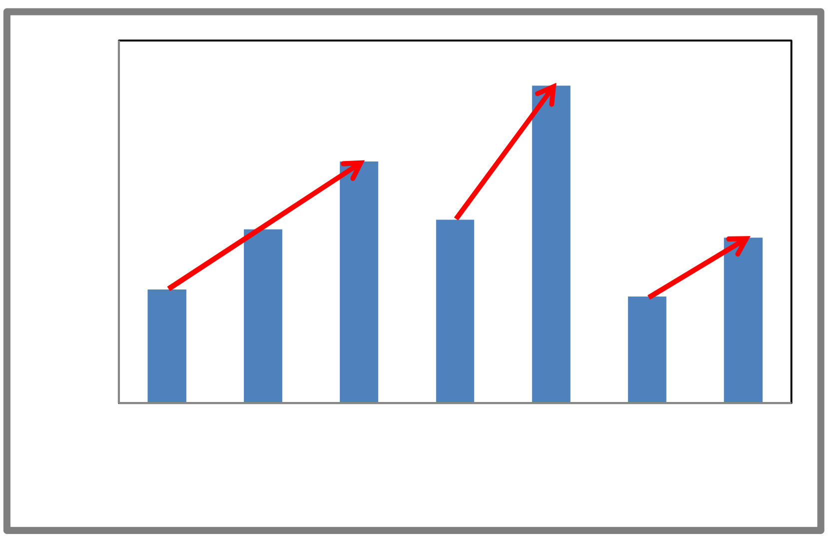


Fig. 10. Effect of initial melt temperature, gap size and preheating temperature on melt penetration.

5. Conclusions

1- The model can predict the amount of weld penetration in a relatively good agreement with experimental data.

2- Increasing melt temperature as well as weld gap and preheating temperature increase the temperature of all rail points. It seems that the effect of weld gap is greater.

3- To have stable weld penetration, maximum possible weld gap is recommended.

Acknowledgment
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