Influence of Heating Frequency on Residual Oxide in Joining With Induction Heating

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Keywords: Rolling, Strip rolling, Joining, Experimental analysis, Numerical analysis, FEM, Model simulation

INTRODUCTION

Recently, in response to increasing needs for auto body weight reduction by reducing the thickness of automotive steel sheets, high tensile strength steel sheets with high strength and excellent workability have been developed and manufactured. Alloying elements such as silicon (Si) and manganese (Mn) are added to these steels for strength improvement, but many problems occur in the manufacturing process as addition increases. In the rolling process, the manufacturable size is limited by the increase in deformation resistance, and in particular, it is difficult to manufacture thin materials from the viewpoint of sheet passing stability.

No. 3 hot strip mill at JFE Steel's East Japan Works (Chiba District) has an endless rolling facility, which enables continuous finish rolling of multiple coils by joining the coils by upsetting the end faces of hot-rolled sheet bars after induction heating [1]. Endless rolling is also useful for manufacturing high tensile strength steel, since there are few sheet passing problems at the leading edge when rolling thin materials. However, continuous rolling has not been applied to high tensile strength steel because of the insufficient bonding strength between the sheet bars. In addition to induction heating, there are other joining techniques for hot-rolled sheet bars, such as laser welding [2] and shear joining [3-5], but to the best of our knowledge, no reports concerning the application of these methods to high tensile strength steel have appeared in the literature.

When joining hot-rolled sheet bars, it is important not to leave a surface oxide on the bonding interface. In high tensile strength steel containing elements [6-7] such as Si and Mn, which form more stable oxides than Fe, reduced bonding strength due to the presence of residual oxides is a problem. As a countermeasure for residual oxides at the bonding interface, a method for promoting plastic flow in the center of the plate thickness by performing groove processing at the bonding interface in ERW pipe welding has been proposed [8].

However, no studies have examined the oxide discharge behavior when joining sheet bars with a large cross section in the high temperature region, as in the case of endless rolling, and the factors that influence joint strength have not been clarified. In our previous studies, we investigated the effects of the bonding interface temperature and material components on bonding strength [9-10]. In addition, it is also conjectured that oxide discharge behavior may be affected by changes in the temperature distribution near the joint at different heating frequencies. Therefore, in this paper, the effect of the heating frequency on joint strength is investigated by numerical analysis.

NUMERICAL SIMULATION MODEL

In order to verify the effect of the heating frequency in induction heating on residual oxides, the discharge behavior of oxides during upsetting was evaluated by a numerical analysis using the thermal fluid analysis software FLUENT. Fig. 1 shows the outline of the created model. An oxide with a thickness of 0.1 mm was placed at the joining interface, and the behavior of the oxide when the sheet bar was pressed against a rigid wall was evaluated by a two-dimensional model of the sheet bar cross section after the heating. The VOF (Volume of Fraction) method was used as a multi-phase flow model to calculate the interface position of each phase. The physical properties of the oxides are shown in Table 1.

The temperature change during upsetting was also calculated assuming that the part in contact with the rigid wall is adiabatic, the temperature of the right face in the Fe region in Fig. 1 is constant from the initial temperature, and the temperatures of the upper and right end faces in the air region are constant at 25 °C. The region of Fe above 1 480 °C was treated as a liquid phase.

The initial temperature distribution was obtained by calculating the temperature during induction heating using a coupled electromagnetic field and heat conduction analysis. Calculations were made for cases in which the dimensions of the sheet bar were 37.5 mm in thickness × 1 000 mm in width and there were two conditions for the heating frequencies. The calculated temperature distribution is shown in Fig. 2. It can be confirmed that the temperature distribution is different due to the difference in the heating frequency.

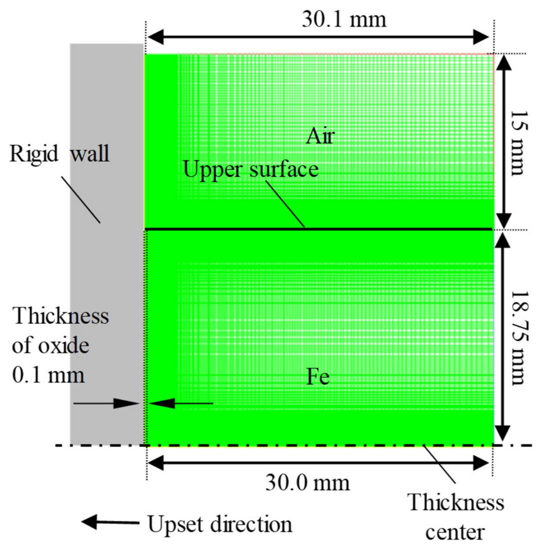
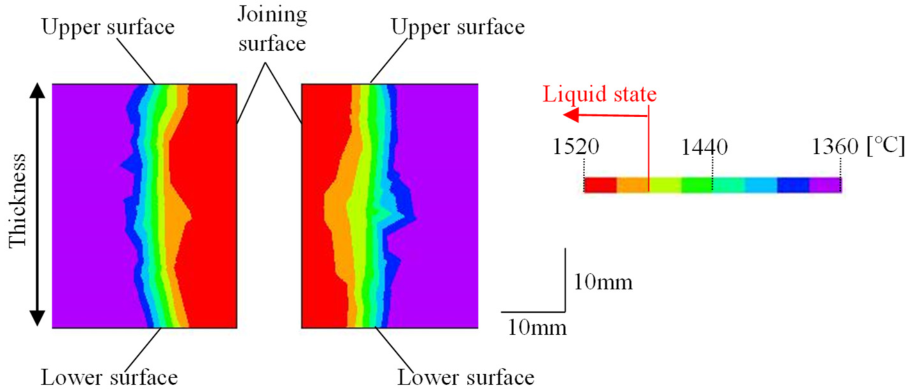


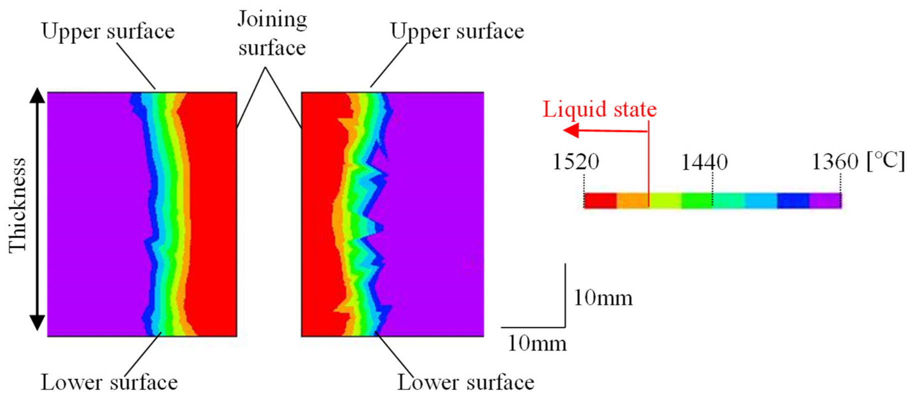
Figure 1. Configuration of numerical model with mesh.

Table 1. Properties of oxide.

Density	Thermal conductivity	Viscosity
kg/m^3	W/(m·°C)	Pa·s
4500	5	0.005



(a) Low induction heating frequency.



(b) High induction heating frequency.

Figure 2. Initial temperature distribution.

ANALYSIS RESULTS

Fig. 3 shows the change in the ratio of the residual oxide with respect to the amount of upset. The ratio of the amount of residual oxide to the amount of oxide in the initial state was evaluated. The residual oxide was defined as the oxide present in the center of the sheet bar thickness rather than at the surface of the initial thickness. At both heating frequencies, the residual amount of oxide in the final state was less than 0.1 % of that in the initial state. When the upsetting amount was about 13.5 mm or less, the residual amount of oxide was smaller at the high heating frequency, but when the upsetting amount was more than about 13.5 mm, the residual amount was smaller at the low heating frequency.

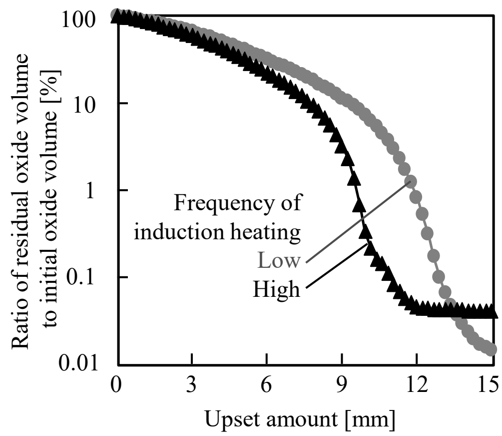


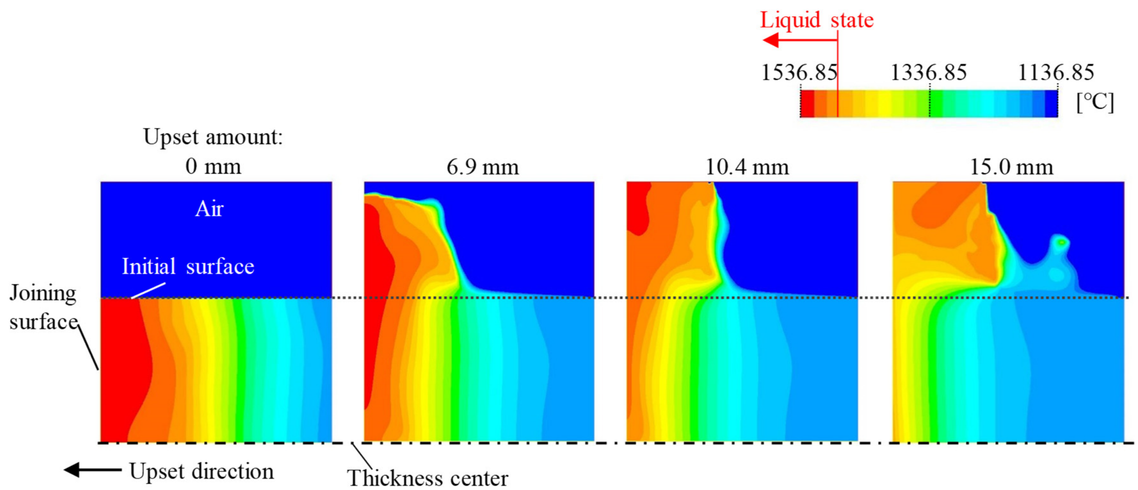
Figure 3. Residual oxide volume between surfaces.

DISCUSSION

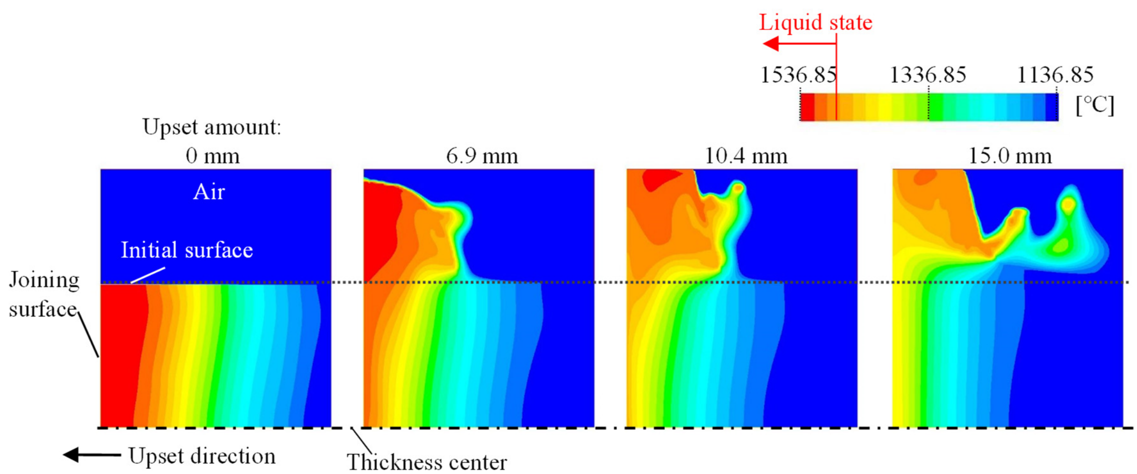
First, the initial temperature distribution shown in Fig. 2 will be discussed. At the low heating frequency, the length of the melting range from the joining surface (referred to as the melting depth) is larger at the center of the sheet bar thickness and becomes smaller toward the upper and lower surfaces. On the other hand, when the heating frequency is high, the melting depth at the center of thickness becomes small, and the melting depth near the upper and lower surfaces becomes large. This difference is considered to be due to the feature that the current is more concentrated at the end when the material is heated at a higher frequency.

Next, the change in the oxide volume fraction shown in Fig. 3 will be discussed. The temperature distribution during upsetting is shown in Fig. 4. At the high heating frequency, the molten part is discharged out of the steel thickness region of the initial state in the early stage of upsetting (i.e., when the upsetting amount is about 13.5 mm or less). It is considered that the large melting depth near the upper and lower surfaces ensures a discharge path for the molten steel to the upper and lower surfaces. As a result, it is thought that an effect similar to that of a groove occurs [8], and when the upsetting amount is small, the oxide is more easily discharged at the high heating frequency.

Fig. 5 shows the liquid phase fraction distribution at an upsetting amount of 15 mm. At the low heating frequency, a melted portion exists near the crimping surface, but at the high heating frequency, the melted portion is almost nonexistent. At the high heating frequency, the molten steel was discharged at an earlier stage of upsetting due to the smaller melting depth at the center of thickness, and the fluidity of the oxide during upsetting was reduced, which made it difficult to discharge the oxide. On the other hand, at the low heating frequency, where the molten portion is likely to remain, oxide discharge continued even when the upsetting amount was large, and as a result, the final remaining amount was smaller than at the high heating frequency.

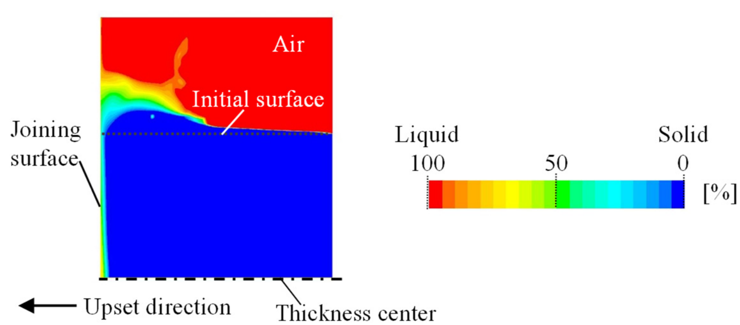


(a) Low induction heating frequency.

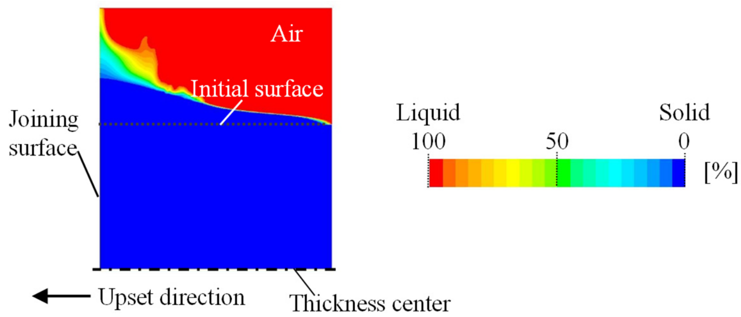


(b) High induction heating frequency.

Figure 4. Temperature distribution during upsetting.



(a) Low induction heating frequency.



(b) High induction heating frequency.

Figure 5. Liquid phase ratio distribution (Upsetting amount: 15.0 mm).

CONCLUSIONS

The effect of the heating frequency in induction heating on the oxide residue during joining of sheet bars was investigated numerically with the aim of developing an endless rolling technology for high tensile strength steel. The FEM flow analysis results showed that a higher heating frequency resulted in less remaining oxide when the upsetting amount was small. It is estimated that the higher temperatures near the top and bottom surfaces of the joining interface promoted oxide discharge. However, oxide discharge was not observed when the upsetting amount exceeded a certain level. In this case, it was suggested that the temperature near the center of the sheet bar thickness was low, so there was little liquid phase, and the flow of oxides stopped.

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