Reduction of Residual Stress in Hot Rolled H-beams*

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Synopsis
In hot rolled H-beams, putting heat-insulator on the upper surface of the web (web-insulating) and cooling the outer surface of the flange by water (flange-cooling) after the finishing rolling are considered effective measures for reducing the residual stress. To confirm this, the relation between the residual stress and the times of their treatments under various finishing temperature conditions was investigated using an analytical method for the thermal stress. This method is characterized by taking phase transformation into consideration.

The outline of results obtained is as follows:

1) The longer the times of the web-insulating or of the flange-cooling are and the smaller the difference in finishing temperature between the flange and web is, the smaller the tensile residual stress in the flange and the compressive residual stress in the web are. Namely the residual stress is reduced in all cross-sectional areas in these cases.

2) In the case of a typical large size H-beam (H: 900 × 300 × 16 × 28 mm), the time of the flange-cooling (heat transfer coefficient during water-cooling: 259 kcal/m²·h·°C) after rolling for reducing the residual stress in the web is about a quarter of that of the web-insulating.

3) It is possible to reduce the residual stress below a required value by combining the control of the difference in finishing temperature with the control of the difference in cooling rate between the flange and web after rolling.

4) The choice of either web-insulating or flange-cooling after rolling should be made by considering the influence on the metallurgical quality and the ease of control as well as the effect of reducing the residual stress.

I. Introduction
The residual stress in hot rolled H-beams is caused by the difference in finishing temperature between the flange and web, and the difference in cooling rate after the finishing rolling. In general, the residual stress is tension in the flange and compression in the web. The larger the thickness ratio of flange to web (t_f/t_w) is, the larger the residual stress is. Large size H-beams of 600～900 mm in the web height and 300 mm in the flange width, in which the value of (t_f/t_w) is high, have large residual stress and the following problems often arise:
1) The occurrence of inferior goods which are buckled in the web
2) The occurrence of shape defects and cracks by releasing or redistributing the residual stress during the secondary deformation
3) The lowering in proof strength as structural materials.

In order to reduce the residual stress, it is necessary to decrease the difference in finishing temperature and the difference in cooling rate after the rolling. For this purpose, the following measures have been suggested[1～3]:

1) Covering the web with heat-reflector (web-reflecting) or cooling the outer surface of the flange by water (flange-cooling) before the finishing rolling
2) Putting heat-insulator such as asbestos on the upper surface of the web (web-insulating) or flange-cooling[4,5] after the finishing rolling
3) Shortening the distance between H-beams cooled in the I-shape form on the cooling bed.

As in order to control the residual stress below a required value using these measures, however, it is necessary to investigate quantitatively their effects on the residual stress. In the previous report[4,5], the influence of the finishing temperature on residual stress of H-beams air-cooled after rolling was investigated in detail using a numerical method[6] for analyzing the thermal stress. This method has been developed by the author and is characterized by taking phase transformation into consideration. As a result, it has become clear that even if the difference in finishing temperature is small, the residual stress does not reduce sufficiently. Therefore in order to reduce the residual stress sufficiently, it is considered to be necessary to combine the control of the difference in finishing temperature with the control of the difference in cooling rate after rolling. In this report, the relation between the residual stress and the treatment times of the web-insulating or of the flange cooling after rolling under various finishing temperature conditions was investigated using the analytical method.

II. Outline of Calculation Method
As the calculation method has been reported previously[4,5], only the outline is described here.

The cross-sectional temperature distribution is calculated by solving the two-dimensional Fourier's equation, where the longitudinal heat flow is ignored and the generating heat by phase transformation is taken into consideration, using a special finite difference method called the IAD method[6]. In the case of the calculation of stress and strain, only the longitudinal direction is taken into account and it is assumed that the cross-section keeps a plane during cooling, because rolled H-beams are long and thin. Material properties necessary for their calculation, such as specific heat, thermal conductivity, coefficient of thermal linear expansion and yield stress, are not only functions of temperature, but also functions of phase transformation ratio. Therefore the calculation of phase transformation is carried out simultaneously. The

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transformation is calculated by a method which utilizes a time-temperature-transformation (TTT) diagram for the estimation of the transformation in an arbitrary cooling curve.

III. Web-insulating

1. Comparison between Measured and Calculated Values

Immediately after the finishing rolling, heat-insulator of about 50 mm thickness was put on the upper surface of the web of a large rolled H-beam, the cross-sectional size of which is 808 mm in the web height, 302 mm in the flange width, 16 mm in the web thickness and 30 mm in the flange thickness (H: 808 x 302 x 16 x 30 mm). The H-beam was cooled in this situation till it reached room temperature. Figure 1 shows the comparison between calculated and measured cooling curves at points on the outer surface at the center of the flange and on the upper surface at the center of the web, and shows the comparison between calculated and measured residual stresses across the cross-section. Here, the value of the heat transfer coefficient during the web-insulating in the calculation is a half of the value of that during air-cooling, which is given as a sum of a term of radiation dependent on temperature and a term of convection (7.5 kcal/m²h°C). As shown in the figure, the calculated values of both cooling curves and residual stresses agree well with the measured values.

2. Calculation Conditions

A typical large H-beam (H: 900 x 300 x 16 x 28 mm) was selected as an object of the investigation, because various problems often occur for the large residual stress in this H-beam. As for the finishing temperatures in the flange and web (Tf₀ and T₀), three conditions were selected: case 1 (Tf₀=900 °C, T₀=700 °C), case 2 (Tf₀=900 °C, T₀=750 °C) and case 3 (Tf₀=800 °C, T₀=700 °C). The usual finishing temperature condition in this H-beam is case 1 or case 2. The finishing temperature condition of case 3 is on the premise that the flange-cooling or the web reflecting are carried out between the roughing and the finishing mills. It was supposed that the web-insulating was carried out immediately after the finishing rolling and then the insulating-time was between 0 (air-cooling) and ∞ (room temperature).

3. Calculation Results

As typical examples of calculation results, changes in the temperature, thermal stress, plastic strain and ratio of phase transformation (mean values in thickness), of points at a quarter of the flange width and at a half of the web height, during cooling after the finishing rolling are shown in Fig. 2. Here, the finishing temperature condition is case 1 and the insulating-times are ① 0 min (air-cooling), ② 5 min and ③ ∞ (till it reaches room temperature). Figure 3 shows the calculated values of the residual stress (mean values in thickness) across the cross-section in the same condition as Fig. 2. Figure 4 shows the relation between the residual stress and the insulating-time under various finishing temperature conditions.

The calculated results are as follows:

(1) The longer the insulating-time is, the slower the cooling-rate and the rate of phase transformation in both the flange and web are. The influence of the web-insulating on the temperature in the flange, however, is much smaller than that on temperature in the web.

(2) The thermal stress during cooling shows three changes of tension → compression → tension in the flange and compression → tension → compression in the web irrespective of the insulating-time. The maximum and minimum values of the thermal stress during cooling in the flange and web, and their occurrence periods, however, are affected by the insulating-time.
Fig. 2. Changes in temperature, thermal stress, plastic strain, and ratio of phase transformation (mean values in thickness) during cooling after the finishing rolling in the case of the web-insulating.

Fig. 4. Relation between residual stress and insulating-time under various finishing temperature conditions.
(3) The first change of the thermal stress (tension in the flange and compression in the web) and the next converse change correspond to the transformation in the flange and web, respectively. Namely, in the area where the rate of the transformation is faster, the compressive stress appears and in the area where the rate is slower, the tensile stress appears. This is because the transformation causes both dilatation and generation of heat.

(4) The change of the plastic strain during cooling shows a similar pattern irrespective of the insulating-time. When the transformation proceeds mainly in the web, the plastic deformation is compressive in the web and tensile in the flange. Conversely when the transformation proceeds mainly in the flange, the deformation is compressive there. The amount of plastic strain during cooling in the flange and web, however, is greatly affected by the insulating-time.

(5) The distribution of the residual stress across the cross-section becomes a similar pattern irrespective of the insulating-time and the difference in finishing temperature between the flange and web. The maximum values of the tensile and compressive residual stresses (mean values in thickness) appear at the centers of the flange and web, respectively. The tensile residual stress in the flange becomes smaller as the position approaches the edge and changes into compressive stress at the edge. The compressive stress in the web becomes smaller as the position approaches the fillet and changes into tensile stress in the fillet.

(6) The longer the insulating-time is and the smaller the difference in finishing temperature, the smaller the tensile residual stress in the flange and the compressive residual stress in the web are. Namely the residual stress is reduced in all cross-sectional areas in these cases. Because, when the transformation proceeds mainly in the flange, the longer the insulating-time is, the larger the compressive plastic strain becomes there and the smaller the difference in finishing temperature is, the smaller the difference in thermal contraction between the flange and web from a point immediately after the finishing rolling till a point after cooling (room temperature) becomes.

(7) It is the compressive residual stress in the web that is deeply related to the occurrence of the web-buckling during cooling after rolling and the occurrence of shape defects during the secondary deformation. The insulating-times to control the compressive residual stress in the web below 15 kgf/mm² are about 7.5 min in case 1, 4 min in case 2 and 2 min in case 3.

IV. Flange-cooling

1. Calculation Conditions

The H-beam size and the finishing temperature conditions are the same as those selected in the web-insulating calculation. The flange-cooling is carried out with the following conditions:

- Water cooling time:
  1. 0 min
  2. 1.0 min
  3. 2.0 min

- Insulating time:
  - Case 1: 7.5 min
  - Case 2: 4 min
  - Case 3: 2 min

Fig. 5. Changes in temperature, thermal stress, plastic strain, and ratio of phase transformation (mean values in thickness) during cooling after the finishing rolling in the case of the flange-cooling.
out immediately after the finishing rolling. Then, the outer surface of the flange is cooled homogeneously by water and the heat transfer coefficient by water \( (H_f) \) is 250 kcal/m²·h·°C. This value of \( H_f \) was decided by considering the prevention of the lowering in elongation caused by the extraordinary phase, such as bainite and martensite, and the ease of the uniform cooling control.

2. Calculation Results

As typical examples of calculation results, changes in the temperature, thermal stress, plastic strain and ratio of phase transformation, of points at a quarter of the flange width and at a half of the web height, during cooling after the finishing rolling are shown in Fig. 5. Here, the finishing temperature condition is case 1 \( (T_{f0}=900 ^\circ C, T_{wo}=700 ^\circ C) \) and the water-cooling times are ① 0 min (air-cooling), ② 1 min and ③ 2 min. Figure 6 shows the calculated values of the residual stress (mean values in thickness) across the cross-section in the same condition as Fig. 5. Figure 7 shows the relation between the residual stress and the water-cooling time under various finishing temperature conditions.

The calculated results are as follows:

(1) The longer the water-cooling time is, the faster the cooling-rate and the rate of phase transformation in the flange are.

(2) The thermal stress during cooling shows three changes of tension → compression → tension in the flange and compression → tension → compression in the web irrespective of the water-cooling time. The maximum and minimum values of the thermal stress during cooling in the flange and web, and their occurrence periods, however, are affected by the water-cooling time.

(3) The change of the plastic strain during cooling shows a similar pattern irrespective of the water-cooling time. When the transformation proceeds mainly in the web, the plastic deformation is compressive in the web and tensile in the flange. Conversely when the transformation proceeds mainly in the flange, the deformation is compressive there. The amount of

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**Fig. 6.** Residual stresses (mean values in thickness) across the cross-section in the case of the flange-cooling.

**Fig. 7.** Relation between residual stress and water-cooling time under various finishing temperature conditions.
plastic strain during cooling in the flange and web, however, is greatly affected by the water-cooling time.

(4) The distribution of the residual stress across the cross-section becomes a similar pattern irrespective of the water-cooling time and the difference in finishing temperature between the flange and web. The maximum values of the tensile and compressive residual stresses (mean values in thickness) appear at the centers of the flange and web, respectively. The tensile residual stress in the flange becomes smaller as the position approaches the edge and changes into compressive stress at the edge. The compressive stress in the web becomes smaller as the position approaches the fillet and changes into tensile stress in the fillet.

(5) The longer the water-cooling time is and the smaller the difference in finishing temperature, the smaller the tensile residual stress in the flange and the compressive residual stress in the web are. Namely, the residual stress is reduced in all cross-sectional areas in these cases. Because, when the transformation proceeds mainly in the flange, the longer the water-cooling time is, the smaller the compressive plastic strain becomes there and the smaller the difference in finishing temperature is, the smaller the differences in thermal contraction between the flange and web from a point immediately after the finishing rolling till a point after cooling (room temperature) becomes.

(6) The water-cooling times to control the compressive residual stress in the web below 15 kgf/mm² are about 2 min in case 1, 1 min in case 2 and 0.5 min in case 3.

V. Comparison between Web-insulating and Flange-cooling

The advantage and disadvantage in the use of the web-insulating after the finishing rolling were compared with those in the use of the flange-cooling. The result mentioned above shows that the treatment time for reducing the residual stress in the web using the flange-cooling method is about a quarter of the time using the web-insulating method. In the case of the flange-cooling, however, it is difficult to cool the flange uniformly in the longitudinal and transverse directions, and to prevent the water from intruding onto the web. The lack of uniform cooling causes the fluctuation of metallurgical qualities, such as strength and elongation, and in the case of the existence of the extraordinary metallurgical structure the extreme lowering in elongation occurs. Besides, the intrusion of the water to the web weakens the effect of reducing the residual stress by the flange-cooling. On the other hand, in the case of the web-insulating the insulating-time for reducing the residual stress is longer than the time of the flange-cooling and there are extra processes of putting heat-insulator on the web and of removing it. The warming effect in the web, however, does not change under the existence of insulator over 10 mm in thickness, and then it is possible to warm the web uniformly in the longitudinal and transverse directions without any special precautions. Therefore the fluctuations of the metallurgical qualities and of the residual stress become small.

VI. Conclusion

In hot rolled H-beams, putting heat-insulator on the upper surface of the web (web-insulating) and cooling the outer surface of the flange by water (flange-cooling) after the finishing rolling are considered effective measures for reducing the residual stress. To confirm this, the relation between the residual stress and the times of their treatments under various finishing temperature conditions was investigated using an analytical method for the thermal stress, which is characterized by taking phase transformation into consideration. The results obtained are as follows:

(1) The thermal stress during cooling shows three changes of tension → compression → tension in the flange and compression → tension → compression in the web irrespective of the treatment times of the web-insulating or the flange-cooling. The maximum and minimum values of the thermal stress during cooling in the flange and web, and their occurrence periods, however, are affected by their treatment times.

(2) The distribution of the residual stress across the cross-section becomes a similar pattern irrespective of their treatment times and the difference in finishing temperature between the flange and web. The maximum values of the tensile and compressive residual stresses (mean values in thickness) appear at the centers of the flange and web, respectively. The tensile residual stress in the flange becomes smaller as the position approaches the edge and changes into compressive stress at the edge. The compressive stress in the web becomes smaller as the position approaches the fillet and changes into tensile stress in the fillet.

(3) The longer the treatment times of the web-insulating or the flange-cooling are and the smaller the difference in finishing temperature, the smaller the tensile residual stress in the flange and the compressive residual stress in the web. Namely the residual stress is reduced in all cross-sectional areas in these cases.

(4) In the case of a typical large size H-beam (H: 900 × 300 × 16 × 28 mm), where various problems often occur for the large residual stress, their treatment
times to control the compressive residual stress in the web below 15 kgf/mm² are the following:

i) The treatment time of the web-insulating
   Case 1 \( (T_{fo}=900 \, ^\circ C, T_{wo}=700 \, ^\circ C) \rightarrow 7.5 \) min
   Case 2 \( (T_{fo}=900 \, ^\circ C, T_{wo}=750 \, ^\circ C) \rightarrow 4 \) min
   Case 3 \( (T_{fo}=800 \, ^\circ C, T_{wo}=700 \, ^\circ C) \rightarrow 2 \) min

ii) The treatment time of the flange-cooling (heat transfer coefficient during water-cooling: 250 kcal/m²·h·°C)
   Case 1 \( \rightarrow 2 \) min Case 2 \( \rightarrow 1 \) min Case 3 \( \rightarrow 0.5 \) min

Namely the treatment time for reducing the residual stress in the web using the flange-cooling method is about a quarter of the time using the web-insulating method.

(5) It is possible to reduce the residual stress below a required value by combining the control of the difference in finishing temperature with the control of the difference in cooling rate between the flange and web after rolling.

(6) The choice of either web-insulating or flange-cooling after rolling should be made by considering the influence on the metallurgical quality and the ease of control as well as the effect of reducing the residual stress.

REFERENCES