Features of Thermal Stress Generated by Welding & Cutting under Loading †

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Abstract

Steels, which are generally used for bridge structures, have characteristics such that they are apt to corrode quickly. So, it is frequently expected that steel bridges, which have been damaged by increase of vehicle load and corrosion, need repair or strengthening. Repair or strengthening is generally accompanied by cutting, bolting and welding procedures. However, the basic characteristics of stress and distortion generated by cutting and welding for the repair work are not yet enough understood. The safety of the structure following welding repair is confirmed by existing safety evaluation methods. So, in order to gain more confidence and accumulate a fundamental data about the safety of the structure after welding repair, the distribution and magnitude of thermal stresses generated by welding and cutting are generalized. The influence of applied load with respect to stress generated by welding and cutting has been investigated.

KEY WORDS : (Repair welding),(Thermal Stress), (3D Elastic-Plastic FEA), (Heat Source)

1. Introduction

Steels, which are usually used for structures such as bridges, marine structures, towers, pipes, vessels, and so forth, have characteristics that are apt to promote corrosion quickly. It is frequently expected that steel bridges, which have been damaged by an increase of vehicle load, corrosion and so on, need repair or strengthening.

There are a number of methods to repair damaged steel structures. These repair or strengthening methods generally are accomplished by cutting, bolting and welding procedures. These repair or strengthening methods have both merits and shortcomings.

Among these methods, the welding repair method, which has merit such as high degree of freedom of repair shape, good transmission of force and good appearance, is considered. Confidence about the safety of the structure during work and after work must be established to avoid safety problems at work due to a loss of stiffness. But, it is difficult to confirm the safety of the structure after repair welding using existing safety evaluation methods. A proper evaluation method of the load-carrying-capacity in order to confirm the safety of the structure following repair welding is proposed. There are several existing methods to evaluate the load-carrying-capacity of a structure. Among these methods, a method with an allowable stress design theory is usually used in steel structures. But, this method takes no account of heating due to cutting and welding during repair procedures. With a stress correction coefficient with respect to heating, an evaluation of load-carrying-capacity would have been possible during the welding repair work.

Therefore, stress generated by heating such as cutting and welding is generalized in order to decide a correction coefficient with respect to heating under load.

2. Feature of Stress Generated by Welding

In general, the influence of heating on load-carrying-capacity can be determined through the stress feature generated by heating, such as cutting and welding, carried through the analysis.

2.1 General

It is known that the average temperature rise (T_{av}) and the initial temperature (T) are the parameters governing stress generated by heating. It has been shown that the average temperature rise (T_{av}) and heat input (Q) for welding[11),13),14)] are related by :

$$T_{av} = \frac{Q}{2c\rho hB} (℃) \tag{1}$$

$$Q^w = \eta \frac{VI}{v} \times 0.24 (cal/cm) \tag{2}$$

where, c = Specific heat ($cal/℃ \cdot g$),

ρ = Density (g/mm^3),

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Table 1 Welding conditions

No.	V (V)	I (A)	η	v (mm/s)	c $(cal/℃\cdot g)$	ρ (g/mm^3)	h (mm)	B (mm)	T_{av} (℃)
1	30	330	0.85	5	0.13	7.8	8	500	49.8
2	30	265	0.85	5	0.13	7.8	8	500	40
3	30	200	0.85	5	0.13	7.8	8	500	30.2
4	30	240	0.85	5	0.13	7.8	6	500	48.3
5	30	200	0.85	5	0.13	7.8	6	500	40.2
6	30	150	0.85	5	0.13	7.8	6	500	30.2

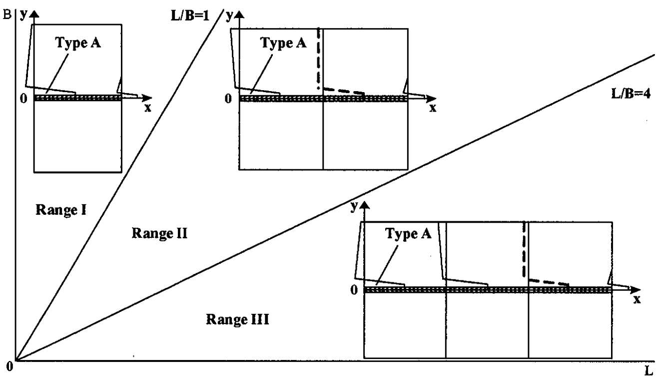


Figure 1. Features of Welding Residual Stress Distribution in Three Ranges of L/B[16)]

$h =$ Thickness (mm),
$B =$ Width(mm),
$V =$ Voltage (V),
$I =$ Current (A),
$v =$ Welding speed ($mm/\sec$)

The steel materials, which are usually used in civil engineering, can be characterized by[13),14)]:

$$B \geq 10^{-2} Q/h \quad \text{or} \quad T_{av} \leq 50 \tag{3}$$

where, $Q =$ Heat input(cal/mm),
$h =$ Thickness(mm),
$B =$ Width(mm)

The welding model, the dimension of length and width of plate, are determined by the pattern of stress distribution, which is classified by the ratio between length and width.[16)] The features of stress according to the ratio between length and width is shown in Fig. 1. In this paper, the dimensions of welding model are limited to Range I. That is to say, the pattern of Type A extends all over the plate length.

Range I	L/B < 1
Range II	1 < L/B < 4
Range III	4 < L/B

2.2 Analysis Model for Welding and Conditions

The 3-D thermal elastic-plastic analysis by the finite element method is carried out for the analysis model as shown in Fig. 2 to determine the features of stress generated by welding.

The 3-D finite element welding analysis is performed by FCAW along the x-direction under the welding conditions shown in Table 1.

2.3 Distribution of Welding Residual Stress

The relation between stress generated by welding and the average temperature rise is shown in Fig. 3. So, σ in Fig. 3 is the proportion of the magnitude of stress generated by welding to yield stress of materials. The subscript stands for the proportion value at each break point. In other words, σ_1 is the proportion of the maximum magnitude of tensile or compressive stress generated by welding, to the yield stress of materials at the first break point. And, Y is the proportion of the distance between each break point and from the welding line to the width of plate.

From Fig. 3, it can be seen that the magnitude of stress σ_1, σ_2 and σ_3 of each break point is proportional to the average temperature rise. So, it can be recognized that the stress generated by welding is generally distributed as in Fig. 4. And, it can be noted that the distance, Y_1, Y_2, and Y_3, between each break point from welding line is proportional to the average temperature rise. The computation of the distance Y was performed using proportional constants. With these results, the distance between each break point from the welding line can be assumed by Eq. (4) and Eq. (5). The Eq. (4) is in good agreement with existing research result.

$$\begin{aligned} Y_{1R} &= 0.6 \times 10^{-3} Q/hB \\ Y_{2R} &= 2.0 \times 10^{-3} Q/hB \\ Y_{3R} &= 11 \times 10^{-3} Q/hB \end{aligned} \tag{4}$$

$$\begin{aligned} Y_{1T} &= 0.8 \times 10^{-3} Q/hB \\ Y_{2T} &= 2.0 \times 10^{-3} Q/hB \\ Y_{3T} &= 11 \times 10^{-3} Q/hB \end{aligned} \tag{5}$$

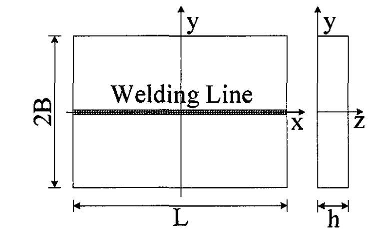
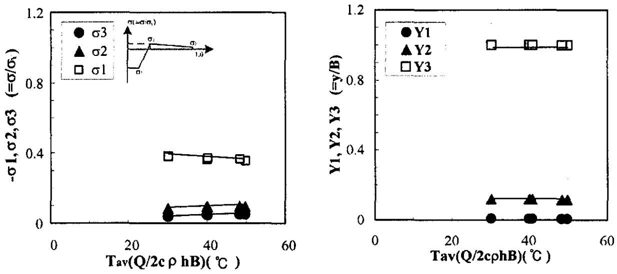
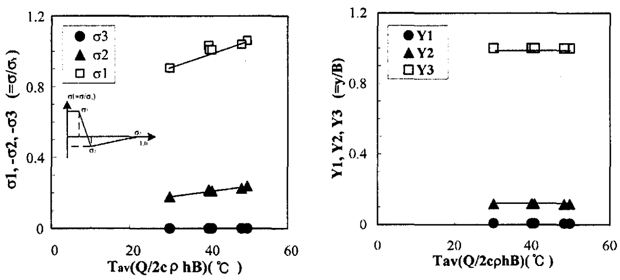


Figure 2. Analysis Model for Welding



(a) Transient Stress



(b) Residual Stress

Figure 3. Effect of the Average Temperature Rise on Welding Stress and Locations

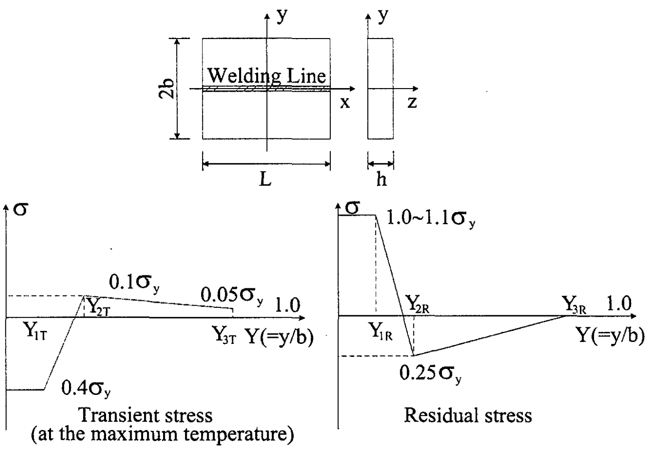


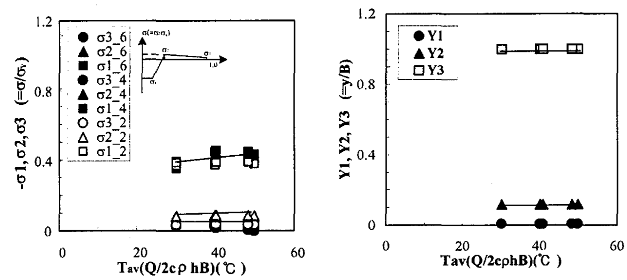
Figure 4. Basic Shape of Distribution of Welding Stress

2.4 Distribution of Welding Residual Stress under Static Load

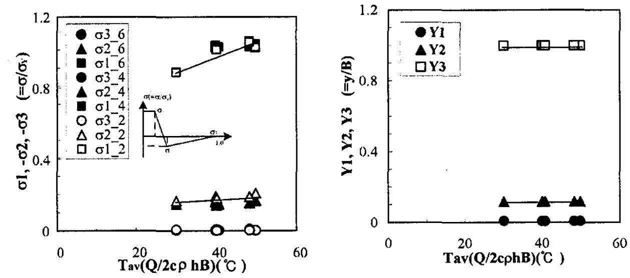
2.4.1 Compressive Load

Figure 5 shows the relation between stress generated by welding under compressive load and the average temperature.

From Fig. 5, the applied compressive load has no effect on tensile stress generated by welding. But, half of the applied compressive load has some influence on the

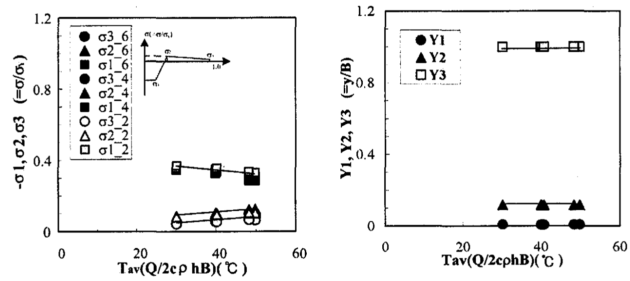


(a) Transient Stress

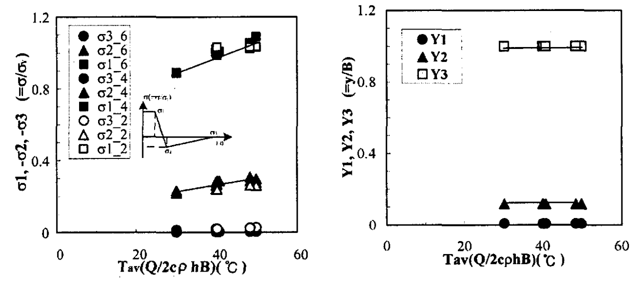


(b) Residual Stress

Figure 5. Effect of the Average Temperature Rise on Welding Stress and Locations under Compressive Load



(a) Transient Stress



(b) Residual Stress

Figure 6. Effect of the Average Temperature Rise on Welding Stress and Locations under Tensile Load

distribution of compressive stress generated by welding. So, it can be recognized that the stress generated by welding under compressive load generally distributed as in Fig 7. It can be found that the distance, Y_1, Y_2, and Y_3, between each break point from the welding line is proportional to the average temperature rise. If the distance Y is calculated using a same method as before, it can be assumed by Eq. (4) and Eq. (5).

Table 2 Cutting conditions

No.	M	T_f (℃)	W_m (mm)	v (mm/s)	c ($cal/℃\cdot g$)	ρ (g/mm^3)	h (mm)	B (mm)	T_{av} (℃)
1	1.25	1450	2	5	0.13	7.8	10	500	9.8
2	1.25	1450	4	5	0.13	7.8	10	500	19.6
3	1.25	1450	6	5	0.13	7.8	10	500	29.3
4	1.25	1450	8	5	0.13	7.8	10	500	39
5	1.25	1450	10	5	0.13	7.8	10	500	48.8

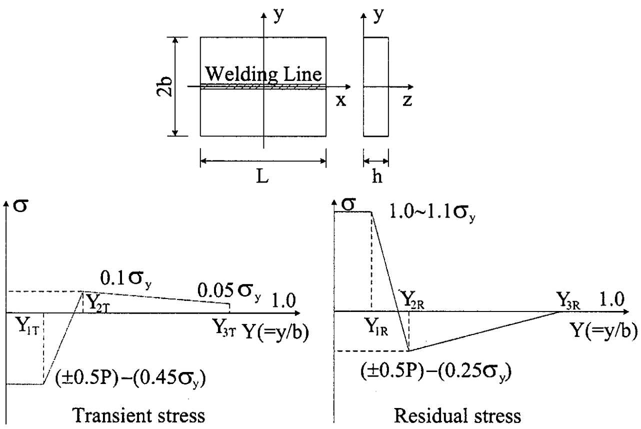


Figure 7. Basic Shape of Stress Generated by Welding under Load

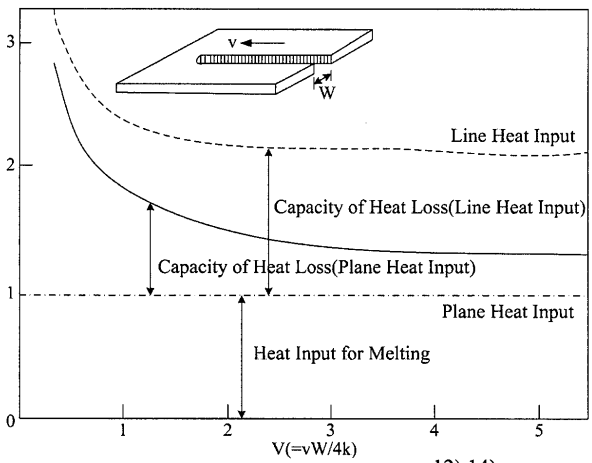


Figure 8. Heat Input for Cutting[12),14)]

2.4.2 Tension Load

Figure 6 shows the relation between stress generated by welding under tension load and the average temperature rise.

In case of the applied tension load, the distributions of tensile stress and compressive stress are similar to those for the applied compressive load. So, it can be recognized that the stress generated by welding under tensile load generally distributed as in Fig 7. The distance Y between each break point and the heat source shows a similar result as before. So, the distance Y is calculated using the same equations, Eq. (4) and Eq. (5), as before.

3. Features of Stress Generated by Cutting

3.1 General

The energy content is the parameter governing cutting capacity. In the case of the same energy content, the magnitude of heat input, namely, cutting width with respect to the size of nozzle is the parameter governing cutting capacity. It can be found that the average temperature rise (T_{av}) and the initial temperature (θ_i) are the parameters governing the stress generated by heating. It has been shown that the average temperature rise (T_{av}) and heat input (Q) for the cutting[12),13),14)] are related by :

$$Q = C\rho vhW_m(MT_f + \frac{H}{\rho})\,(cal/mm) \qquad (6)$$

where, C = Average Specific heat ($cal/℃\cdot g$),

ρ = Density (g/mm^3),

W_m = Average Cutting Width (mm),

$M = Q_b/Q_f$,

T_f = Melting Temperature (℃),

H = Melting Latent Heat (cal/g),

Q_b = Heat Input for Melting (cal/mm),

Q_f = Heat Input to Inject into Base Metal (cal/mm),

v = Welding speed ($mm/\sec$)

Moreover, values for M[12),14)], are summarized in Fig. 8. In this paper, M is taken as 1.25.

The cutting model, the dimension of length and width of plate, is determined using the same method as Chapter 2.

3.2 Analysis Model for Cutting and Conditions

The 3-D thermal elastic-plastic analysis by the finite element method was performed using an analysis model as shown in Fig. 9.

The 3-D analysis is performed for gas cutting along the x-direction under the cutting conditions of Table 2 to investigate the features of stress generated by cutting.

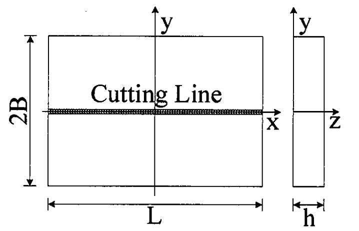
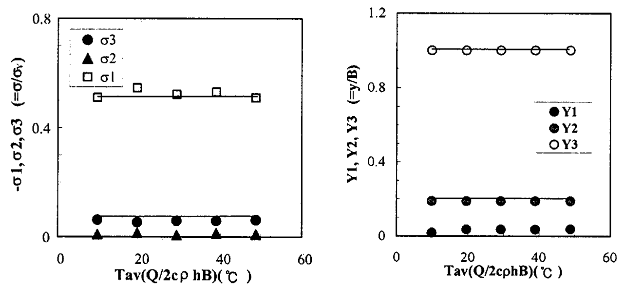
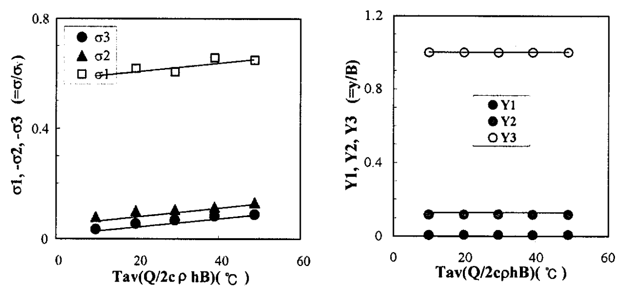


Figure 9. Analysis Model for Cutting



(a) Transient Stress



(b) Residual Stress

Figure 10. Effect of the Average Temperature Rise on Cutting Stress and Locations

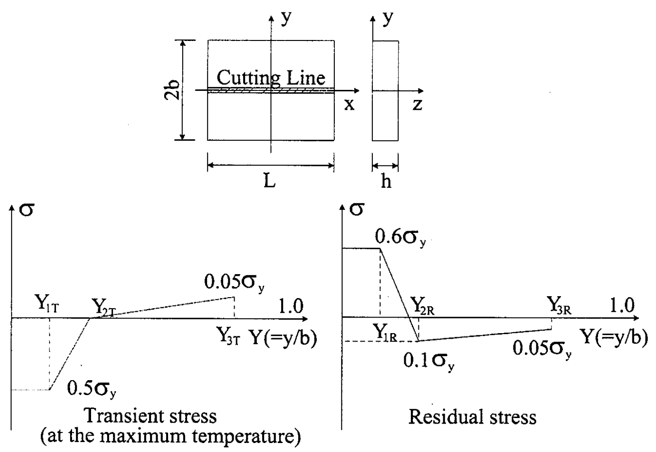


Figure 11. Basic Shape of Distribution of Cutting Stress

3.3 Features of Residual Stress by Cutting

The relation between stress generated by cutting and the average temperature rise is shown in Fig. 10. σ in Fig. 10 is the proportion of the magnitude of stress to yield stress of materials generated by cutting. The subscript is shown for each break point. In other words, σ_2 is the proportion of the magnitude of tensile or compressive stress to yield stress of materials at the second break point generated by cutting. And, Y is the proportion of the distance of each break point from cutting line.

From Fig. 10, it can be seen that the magnitude of stress, σ_1 , σ_2 and σ_3 of each break point is proportional to the average temperature rise. So, it can be recognized that the stress generated by cutting is generalized as in Fig. 11. And, it can be found that the distance, Y_1, Y_2 and Y_3, between each break point from cutting line is proportional to the average temperature rise. The computation of the distance Y is carried out using the same methods as Chapter 2. So, the distance of each break point from cutting line can be calculated by Eq. (7) and Eq. (8).

$$Y_{1T} \,\&\, Y_{1R} = 0.36\times10^{-5} Q/hW_m \tag{7}$$

$$Y_{2T} \,\&\, Y_{2R} = 0.35\times10^{-4} Q/hW_m \tag{8}$$

3.4 Distribution of Cutting Residual Stress under Static Load

3.4.1 Compressive Load

Figure 12 shows the relation between stress generated by cutting under compressive load and the average temperature rise.

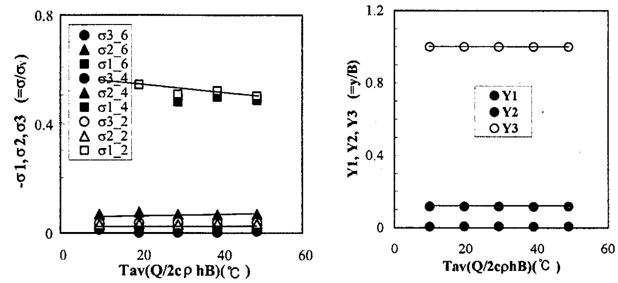
From Fig. 12, the applied compressive load has no effect on the maximum residual tensile stress generated by cutting. But, half of the applied compressive load has some effect on the distribution of the other stress generated by cutting. So, it can be recognized that the stress as generated by cutting under compressive load can be generalized as in Fig 14. And, the same computation method was used in order to calculated the distance Y. So, the distance of each break point from heat source can be calculated by Eq. (9).

$$\begin{aligned} Y_{1TC} &= 0.36\times10^{-5} Q/hW_m \\ Y_{2TC} &= 0.27\times10^{-4} Q/hW_m \\ Y_{1RC} &= 0.36\times10^{-5} Q/hW_m \\ Y_{2RC} &= 0.35\times10^{-4} Q/hW_m \end{aligned} \tag{9}$$

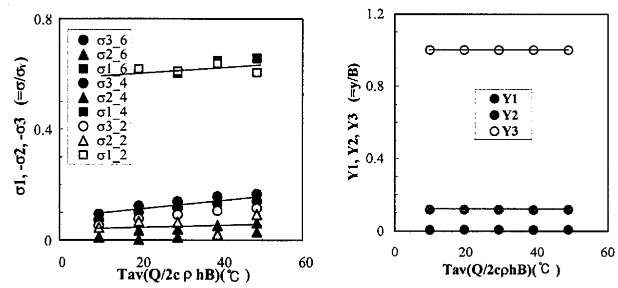
3.4.2 Tension Load

The relation between stress generated by cutting under tension load and the average temperature rise is shown in Fig. 13.

From Fig. 13, the applied tension load has no effect on the maximum tensile residual stress generated by heating such as cutting. But, half of the applied tensile load has some effect on the distribution of the other stresses generated by heating such as cutting. So, it can be recognized that stress generated by cutting under tensile load can be generalized as in Fig. 14. The distance Y of each break point from heat source can be calculated

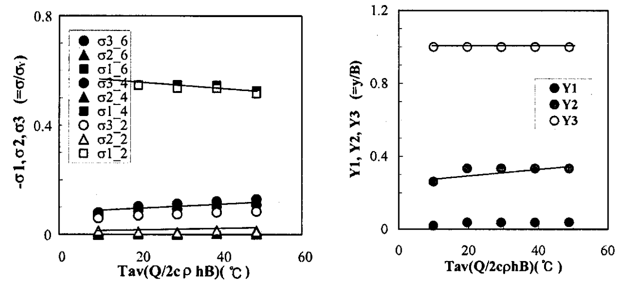


(a) Transient Stress

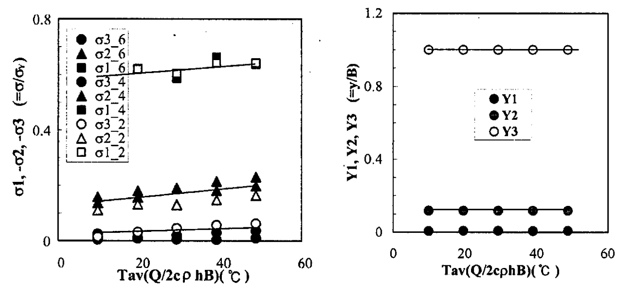


(b) Residual Stress

Figure 12. Effect of the Average Temperature Rise on Cutting Stress and Locations under Compressive Load



(a) Transient Stress



(b) Residual Stress

Figure 13. Effect of the Average Temperature Rise on Cutting Stress and Locations under Tensile Load

from Eq. (10) using the same computation methods as before.

$$
\begin{aligned}
Y_{1TT} &= 0.36\times10^{-5} Q/hW_m \\
Y_{2TT} &= 0.66\times10^{-4} Q/hW_m \\
Y_{1RT} &= 0.36\times10^{-5} Q/hW_m \\
Y_{2RT} &= 0.52\times10^{-4} Q/hW_m
\end{aligned}
\quad (10)
$$

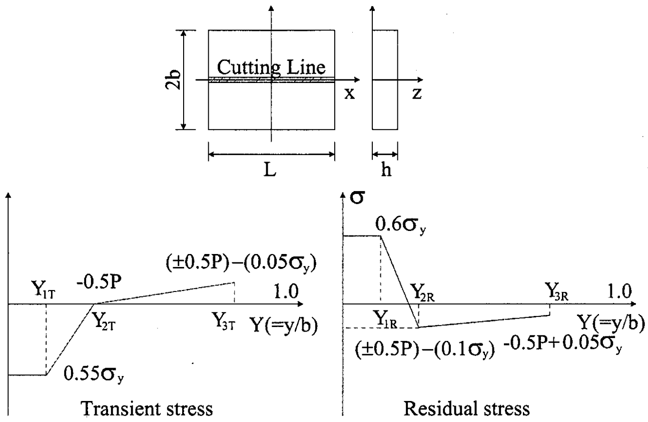


Figure 14. Basic Shape of Stress Generated by Cutting under Compressive Load

4. Conclusions

In this study, the features of stresses generated by welding and cutting have been investigated by 3-D thermal elastic-plastic analysis based on the finite element method. The results obtained can be summarized as follows.

1) The magnitude of stress generated by welding or cutting can be generalized. The distance Y of each break point from the heat source can be formulated.
2) The magnitude of stress generated by welding and cutting under static load can be generalized. The distance Y of each break point from the heat source can be formulated.
3) The applied load has no effect on tensile stress generated by welding. But, half of the applied load has some influence on the distribution of compressive stress generated by heating such as welding
4) The applied load has no effect on maximum tensile residual stress generated by cutting. But, half of the applied load has some influence on the distribution of the other stresses generated by heating such as cutting.

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