FEM Simulation of Gas and Plasma Cutting with Emphasis on Precision of Cutting†

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Abstract

To achieve effective automation or mechanization of a ship structure assembling line, it is necessary to maintain much higher precision in each manufacturing stage, such as cutting and welding, compared to that required for a system which depends on skills of its workers. Since flame cutting is the first stage of assembly and it determines a large part of the accuracy problems, the precision of flame cutting is receiving more attention. Although it has long been considered that residual plastic strain and the motion of the plate due to the transient thermal deformation during cutting are the main causes of cutting error, hardly any studies have been conducted to investigate these factors theoretically and quantitatively. In this paper, a computational method, based on thermal-elastic-plastic FEM, has been developed to simulate the cutting process. The proposed method is verified by comparing the computations with the experimental results obtained for plasma cutting.

Using the FEM model, the residual plastic strain and the motion of the plate due to the transient thermal expansion are computed. Their effects on cutting error are quantitatively discussed. The results show that these factors have great influences on one-side cutting and small effects on two-side simultaneous cutting. The influences of the residual stress existing in the plate before cutting are also investigated.

KEY WORDS: (Gas Cutting) (Plasma Cutting) (Flame Cutting) (Cutting Deformation) (Cutting Error) (Cutting Precision) (Finite Element Method) (Residual Stress)

1. Introduction

The shortage of skilled workers and young labor in the shipbuilding industry has made it increasingly important to speed up automation and mechanization. At the same time, attention has also been given to establishing new assembling processes. Only through appropriate assembling processes can the advantages of mechanization be fully gained.

To realize automation and mechanization in shipbuilding, it is necessary to maintain high precision in all the assembly processes, which are mainly cutting, bending and welding. The cutting process, as the first stage of the entire process, is especially important. Any error introduced in the first stage propagates to the following stages and may result in a big error which is beyond the tolerable limit of automated machines[1)-3)].

Early investigations of the precision of flame cutting[4)-6)] were conducted in the 1950s when the operation of the cutting machine was being changed to the mechanical type. These studies were mostly on the experimental measurements. Afterwards, numerical controlling of the cutting process and plasma cutting were introduced into shipyards. Cutting precision were greatly improved as a result. For quite a long period from then, studies on cutting precision were hardly found except for a few reports concerning the deformation of the thin plate due to cutting[7)]. At the beginning of the last decade, TMCP-type high-strength steel became very commonly used in the industry because of its good strength and toughness. However, its relative high residual stress introduced during the steel-making process caused more errors in the cutting. Several papers have been devoted to this problem[8)].

Although it has long been considered that residual plastic strain and the motion of the plate due to the transient thermal deformation during the cutting are the main causes of cutting error, few studies have been

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Transactions of JWRI is published by Welding Research Institute of Osaka University, Ibaraki, Osaka 567, Japan.

conducted to investigate these factors theoretically and quantitatively. In this paper, a computational method for simulating the cutting process has been developed. The proposed method is verified by good agreement with the experimental results obtained for plasma cutting. Using the FEM model, the residual plastic strain and the plate motion due to the transient thermal expansion are obtained. Their effects are quantitatively discussed. The influences of the residual stress existing in the plate before cutting are also investigated.

2. Numerical Analysis

2.1 FEM Simulation of Cutting Process

The FEM used to simulate the flame cutting, such as gas cutting or plasma cutting, is the same as that used for the simulation of the welding process, which is developed on a thermal-elastic-plastic theory[9]. Although both flame cutting and welding can be considered a thermal-elastic-plastic process, the ways in which the material is filled or removed are exactly opposite. Welding is used to join two separate parts together by filling weld metal into a groove; flame cutting is used for dividing a plate by dropping out the melted metal along the cutting line. The heat from the arc or plasma heats up the metal along the cutting line to the melting point. The molten metal is then blown away by the pressure of the gas flow, and the cutting kerf is formed. Although most heat introduced into the plate goes away with the dropped molten slag, some of the heat dissipates into the plate through conduction. The zone near the cutting line is heated by this heat, and the induced thermal expansion results in cutting deformation. Cutting deformation can be roughly classified into two types: one is the camber, or in-plane warp, which appears in the plane of the plate, and the other is the bucking distortion which belongs to the out-of-plane deformation. Generally, the out-of-plane deformation is the main problem for a thin plate whereas the in-plane deformation often causes troubles in the case of a thick plate.

The FEM method as employed for simulating welding[2] is also used for the simulation of cutting. The transient temperature fields are obtained through solving the heat conduction equation. Stress and deformation are calculated based on the computed temperature fields through thermal-elastic-plastic analysis. The forming of the cutting kerf is simulated as follows. The model of the plate to be cut is meshed as shown in **Fig.1**. In the computation of the temperature field, those elements which are locate in the cutting line are removed from the mesh as soon as the heat source passes. In the computation of the stress and deformation, those elements are turned into so-called dummy elements just after the

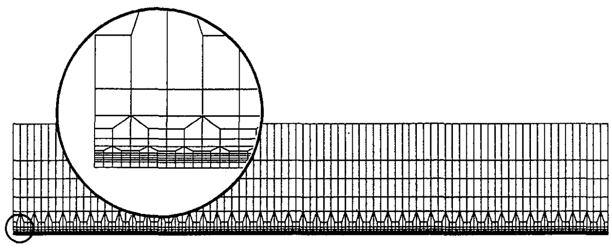


Fig.1 FEM mesh division of a plate to be cut.

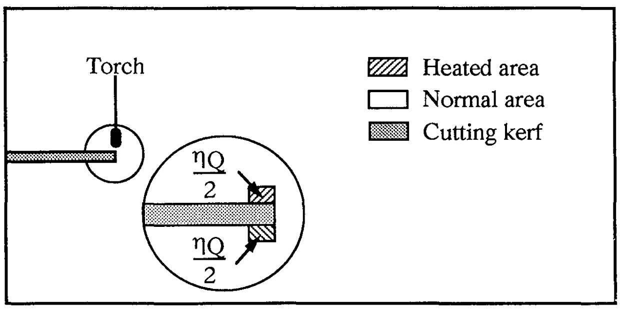
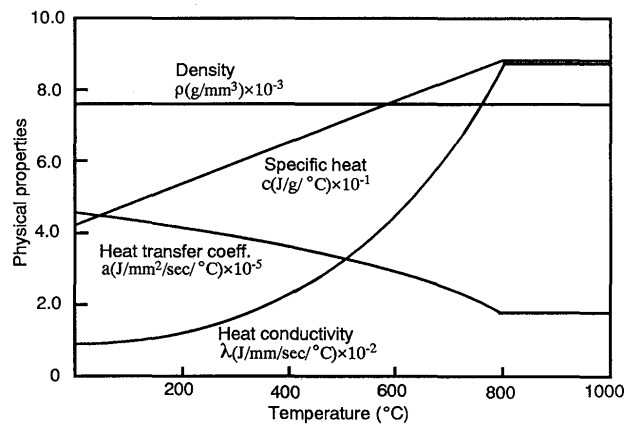
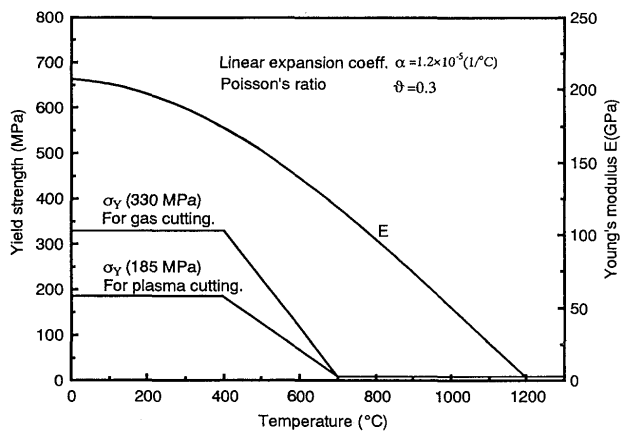


Fig.2 Modelling of cutting.



(a) Thermal properties



(b) Mechanical properties

Fig.3 Material properties of steel.

heat source moves away from the element, as shown in **Fig.2**. The dummy element is a kind of special element whose rigidity is set to be very close to zero. Heat input is given in this way that the net heat input is divided equally and added into the hatched elements along the two lines beside the cutting line. The thermal and mechanical properties used for the computation are shown in **Fig.3**.

All the following computations are carried out on the workstation YHP 9000-735 using a FEM program JWRIN-C93[10], which was developed by the authors' research group specially for the cutting problem involving the techniques discussed above.

2.2 Comparison Between Experimental and Computational Results

To verify the reliability of the proposed method, measurements for plasma cutting on the temperature, bending deformation (camber) and residual stress are taken. The specimens are mild steel with a yield stress of 185 MPa. The plates are rectangular in shape and one of three widths: 60, 80 or 100 mm. The length and the thickness of the plates are 300 mm and 3 mm, respectively. The cutting is completed along the center line of the specimens. The torch is held normal to the plate, and the cutting kerf is 2 mm in width. The cutting conditions are summarized in **Table 1** along with the conditions for gas cutting.

Table 1 Plasma and gas cutting conditions.

Cutting method	Current (Amp)	Voltage (Volt)	Speed (mm/min)	Efficiency (%)	Net heat input (J/mm²)
Gas	100	50	500	17	34.0
Plasma	/	/	400	/	70.5

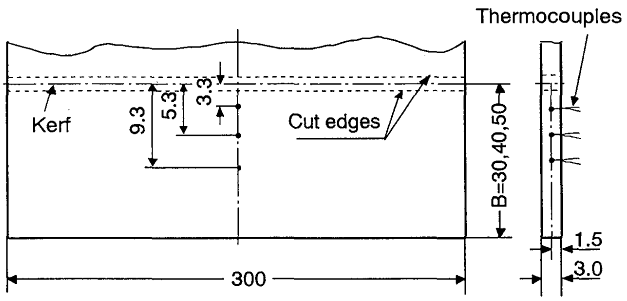
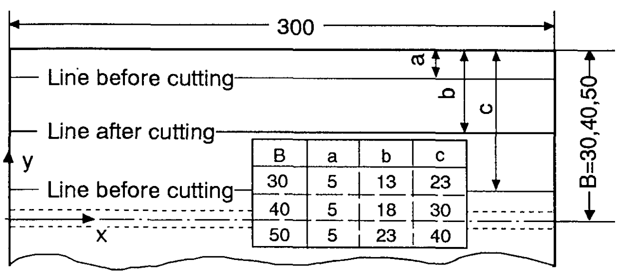


Fig.4 Temperature measurement by thermocouples.



B	a	b	c
30	5	13	23
40	5	18	30
50	5	23	40

Fig.5 Measurement of cutting deformation.

The measurements of the temperature are made in the middle transverse section, as shown in **Fig.4**. Three thermocouples are set at points 3.3, 5.3 and 9.3 mm away from the center line to observe the temperature. The residual stress is obtained by relaxation of the elastic strain through cutting the plate into small pieces. The mean value between the top surface and the bottom surface is used. To measure the deformation, the method shown in **Fig.5** is employed. Two parallel lines are drawn on the plate before the cutting. A third line is drawn between the two lines after the cutting. Taking the newly drawn line as a base line, the relative displacements of the two lines drawn before cutting are observed using a projector-type scale with a magnifier attached. The measured displacements belong to the deformation classified as δ_S, which is caused by the plastic residual strain due to heating and cooling in the cutting process. The details about δ_S will be discussed later in this paper.

The measured temperature is shown in **Fig.6**, and the corresponding computed temperature is shown in **Fig.7**. The zero of the time shown in abscissa corresponds to the time when the arc of plasma reaches the transverse section with thermocouples. **Figure** 8 shows both measured and calculated bending deformations. The plate is deformed

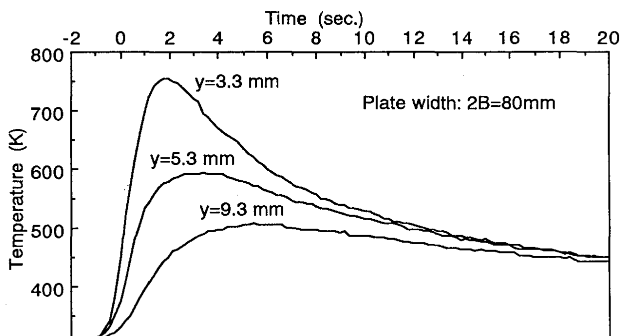


Fig.6 Measured temperature history.

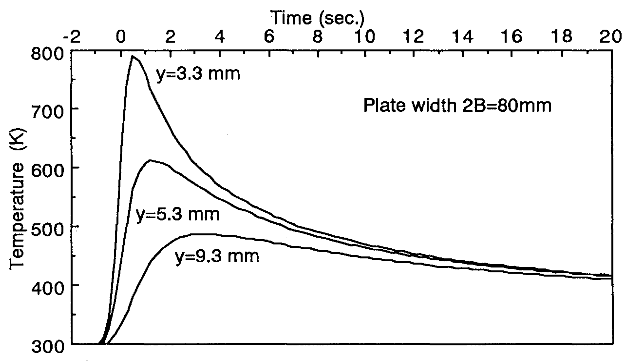


Fig.7 Temperature history computed bye FEM.

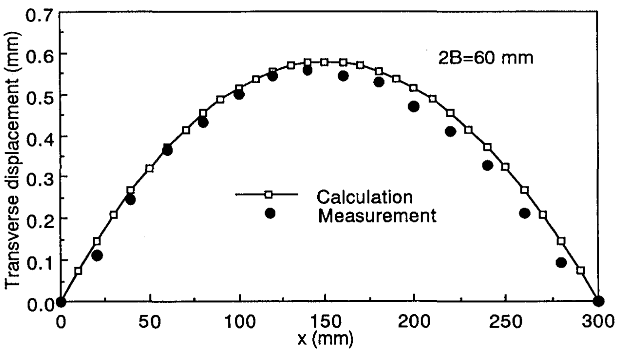


Fig.8 Cutting deformation.

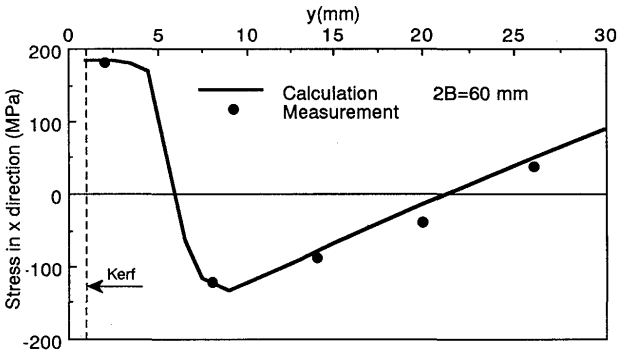


Fig.9 Distribution of residual stress in cutting direction.

into a fan shape. The abscissa indicates the distance from the start point of cutting, whereas the ordinate shows average bending deformation in the y direction. Average bending deformation is the mean value of the displacements measured along the two lines; one is near the cutting line and the other near the outer edge of the plate as shown in Fig.5. It is found that the deformation along the two lines is very similar in both experiments and calculations. **Figure 9** shows the computed residual stress σ_x in cutting direction along the middle transverse section together with the measured values. The stress near the cutting line is high and quite close to the yield stress. But the area with high stress is narrow and about 4 mm according to the computed results. From the good agreement between experiments and FEM calculations, it can be concluded that the FEM is reliable and an effective approach to simulate frame cutting in detail.

3. Factors Influencing Cutting Precision

The factors which affect the cutting precision in NC gas cutting can be classified into the following four groups:

(1) Related to cutting phenomena
- * Accuracy of the torch nozzle.
- * Flame instability caused by variation of the gas pressure and gas flow.
- * Instability of the cutting process itself.

(2) Mechanical cause
- * Straightness of rails.
- * Motion of the cutting machine running on rails.
- * Positioning and operating error of the cutting torches.
- * Accuracy of NC data.

(3) Thermal deformation
- * Deformation due to the residual plastic strain caused by thermal cycle (δ_s).
- * Cutting error due to the deviation of the position of the cutting torch from the planed cutting line (δ_d). This deviation is caused by the transient thermal expansion of the plate just ahead of the torch.
- * Cutting error due to the rigid motion of the plate (δ_m). This kind of motion also causes the torch to deviate from the planed cutting line.

(4) Related to material
- * Residual stress existing in the plate before cutting.

In this paper, only those factors related to thermal deformation and material will be discussed.

Among the factors in the thermal deformation, deformation δ_s, caused by the residual plastic strain existing in the narrow area near the cutting line, has been the main subject of research in the last few decades. It is well known that in one-side cutting, the bending shrinkage δ_s increases linearly with the heat input per unit length q and increases proportionally to the square of the aspect ratio of the plate[11]. The relation can be described as follows:

$$\delta_s = kq(L/B)^2$$

where k is a proportional constant, and q, L and B represent the net heat input per unit thickness and per unit length , the length and the width respectively.

The equation is valid when the width B is wide enough so that the thermal reflection can be ignored.

Other than the residual plastic strain, the deviation of the torch from the planed cutting line is another important cause of cutting error. This kind of deviation results from transient deformation due to thermal expansion in the plate. The transient displacement in the plate can be considered into two types. As classified above, the first is the local thermal deformation ahead of torch (δ_d), and the second is the rigid body motion of the plate (δ_m). If the plate to be cut is placed on an uneven working table, the projecting points from the table support the plate, and they become fulcrum points. The plate tends to move when it is heated during cutting. If the motion is prevented somewhere by friction or a fixing constraint, the plate rotates around these points.

In numerical simulation, the cutting error δ_d is obtained from observing the transient displacements of each point along the cutting line at the time when the torch just passes.

Another important factor in cutting error is the residual stress existing in the plate before cutting. The TMCP-type high-strength steel is considered to carry relatively high residual stress in a large area due to its rolling at a low temperature and its water cooling in the producing process. In the case of such steel, the residual stress may undesirably effect cutting precision.

4. Quantitative Discussion of Error Factors in Gas Cutting

4.1 Models to be Computed and Investigated

To investigate the error factors quantitatively for gas cutting, the four cases shown in **Table 2** have been computed. Case C1 is for two-side simultaneous cutting, and case C2 is for one-side cutting. By comparing these two cases, the effect of the cutting sequence on the cutting error can be clarified. Case C3 and case C4 are used to simulate the cutting phenomena when residual stress exists in the plate to be cut. The trimmed width for cases C1 and C2 is 13 mm, and it is 35 mm for cases C3 and C4. Measurements of the transient displacements during gas cutting have been taken under the same conditions shown in case C1. The comparison between the calculated results and the measured results will be shown later.

Considering geometrical symmetry, half the model is used for cases C1, C3 and C4. For the asymmetric one-side cutting of case C2, the whole model is used.

4.2 Cutting Error in Two-Side Simultaneous Cutting

Figure 10 shows the computed results of cutting errors δ_{sy} and δ_{dy} along the cutting line for the case C1. δ_{sy} is the component of displacement in the y direction which is caused by residual plastic strain. δ_{dy} is the displacement in the y direction caused by transient thermal deformation ahead of the torch. The plate is 8 meters in length and 3 meters in width. Cutting is carried out along the two sides of the plate simultaneously. Error δ_{sy} shows nearly symmetrical distribution along the cutting line with respect to the center of the plate. In the wide area of the central part, δ_{sy} is quite uniform and observed to be about -0.04 mm. Similar to δ_{sy}, the distribution of δ_{dy} is nearly symmetric. The transient thermal expansion causes the breadth of the plate to be trimmed wider. According to the computed results, the increase in trimmed width is about 0.1 mm in the central uniform area. The total cutting error should be the sum of δ_{sy} and δ_{dy}. Except for the start part and end part, the total error is quite uniform and its value is about 0.15 mm. From this result, the error in the central part can be considered to be negligibly small. Since two-side simultaneous cutting is symmetric in geometry, the effects of the residual plastic strain and the transient thermal deformation from one side are cancelled by those from the other side.

Table 2 List of cases for simulation of gas cutting.

Computed cases	Plate size L×W×T (mm×mm×mm)	Cutting position	Residual stress	Experiment	Yield stress (MPa)
C 1	8000×3000×16	Two-side	None	Having	330
C 2	8000×2000×16	One-side		None	
C 3	5000×1000×16	Three-line	Consider		
C 4	5000×2000×16	Two-side			

4.3 Cutting Error for One-side Cutting

The same calculations have been done on the one-side cutting of case C2. The distributions of δ_{sy} and δ_{dy} along the cutting line are shown in **Fig.11**. The cutting error δ_{sy} due to the plastic strain shows a mountain-shape curve with near symmetry along the cutting line. Since the middle part is of a 0.5 mm plus dimension compared to the end sections, quite a large error occurs for the straightness. In this case, the plastic strain exists only on the side along which the cutting is carried out. The

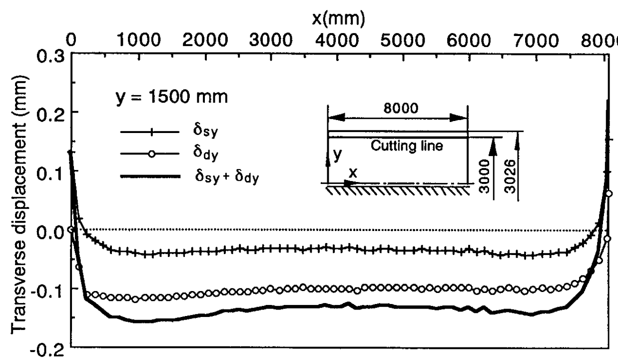


Fig.10 Distribution of cutting error (two-side simultaneous cutting).

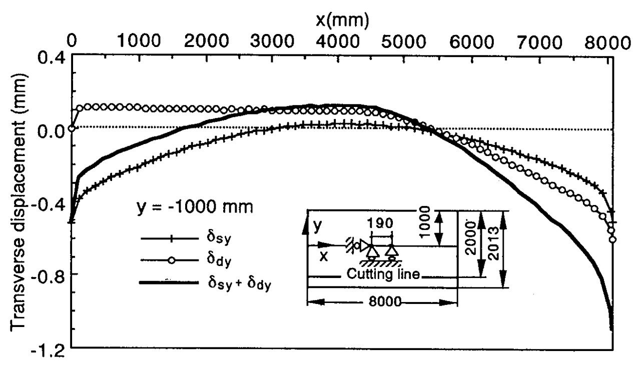


Fig.11 Distribution of cutting error (one-side cutting).

compressive plastic strain makes the plate bend as a beam bends under pure bending moment.

On the other hand, the cutting error δ_{dy}, which is caused by transient thermal expansion just ahead of the torch, shows a very small value before the torch reaches the fixed points at the middle of the plate where the plate is supported as shown in Fig.11. After the torch passes the fixed points, the thermal bending deformation makes the plate moves in the way that δ_{dy} increases quickly. The magnitude of δ_{dy} almost reaches δ_{sy} at the end part of the cutting. Because of these cutting errors, the difference in width between the center and the finishing end after cutting becomes about 1.2 mm, which is much larger than the 0.15 mm in two-side cutting. This kind of error increases with the square of the aspect ratio of the plate as discussed in chapter 3.

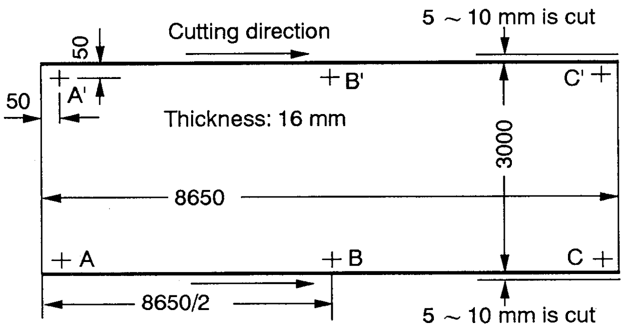
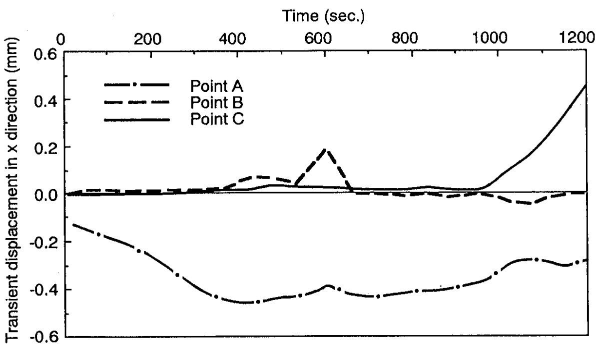
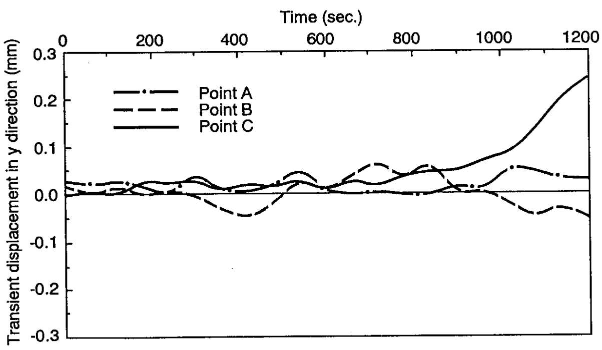


Fig.12 Measurement of transient deformation under gas cutting (case C1).



(a) Displacement in x-direction



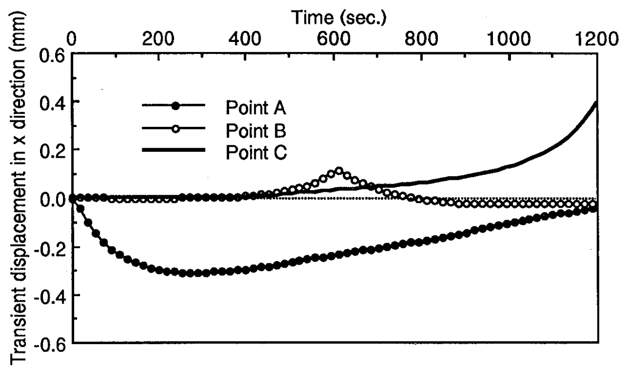
(b) Displacement in y-direction

Fig.13 Measured transient deformation (case C1).

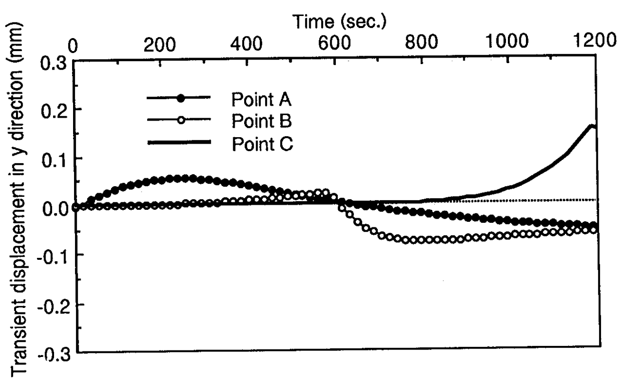
4.4 Comparison with Experimental Results

Transient displacements at six points have been measured for the case C1. **Figure 12** shows the measured positions. On the two lines 50 mm inside of the cutting lines, two points that are 50 mm from each end of the plate and one point in the middle of the plate are chosen. The displacements in three directions x, y and z at these six points are recorded. **Figure 13** shows the measured displacements, and **Fig.14** gives the computed results. The abscissa shows the time period from the beginning to the end of the cutting. From the displacements in x direction (cutting direction), it is observed that the start part moves toward the negative direction of the x axis and the end part moves toward the positive direction as a result of thermal expansion. In the middle of the plate, large displacement was not observed except for the period when the torch was passing near the point. The displacements in the y direction are smaller than those in the x direction, and a big difference is not found between the middle and the end parts. The computed transient displacements show good agreement with the experiments in both tendency and magnitude.

To get a better understanding about the motion of the whole plate, the maximum transient displacements in the



(a) Displacement in x-direction



(b) Displacement in y-direction

Fig.14 Computed transient deformation (case C1).

whole process of cutting are calculated. Figures 15 and 16 show the contour lines of the maximum transient displacements in x and y directions. Significant displacements in the x direction can be found only near the cutting line at the two end parts. The displacements in the y direction are quite uniform along the cutting line. However, the area where the displacement is observed is very narrow, and its maximum value is as small as about 0.15 mm.

4.5 Influence of Rigid Body Motion

To investigate the cutting error δ_m caused by rigid body motion of the whole plate, it is necessary to understand how the plate deforms during cutting. When the displacements caused by thermal expansion or contraction at some positions are fixed due to constraint or friction, translation and rotation of the plate occur. For example, if the points A and B shown in Fig.17 are constrained for some reason, the plate may rotate when the displacements at points A and B are different. The rotation angle β can be written as follows;

$$\beta = \frac{X(v_B - v_A) - Y(u_B - u_A)}{X^2 + Y^2}$$

where u_A, u_B, v_A and v_B are the displacement components in x and y directions at the points A and B. X and Y are the distances between the points A and B in x and y directions.

To compute the rotation angle which varies with time, corresponding transient displacements should be used to calculate β at a specific moment. However, only to determine the upper limit of the rotation, an approximate method using the maximum displacement instead of the exact transient displacement can be employed. In case C1, if the point B, which is on the center line at the start section, is fixed in both x and y directions and the point A near the starting edge of cutting is fixed in the x direction, thermal expansion toward the negative direction of the x axis is prevented, and the plate rotates anticlockwise as shown in Fig.18. A cutting error of about 2 mm would happen at the point C near the end of the cutting, according to the approximate calculation.

However, the real situation is much more complicated. Usually, it is impossible to predict which parts of the plate are fixed due to friction since friction is largely dependent on the surface state of the working table and situation of constraint changes with time. Although the exact motion of the plate is almost impossible to predict, the approximation of β can be used to judge the possible influences of various factors. As shown in Fig.18, large transient thermal deformation can cause a large motion of the plate and result in a large cutting error. Another factor is the aspect ratio L/B. The influence of the rotation increases rapidly with the

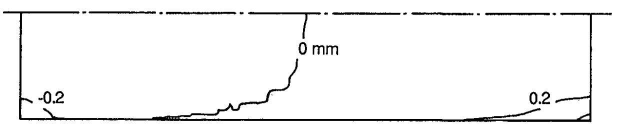


Fig.15 Distribution of maximum transient displacement in x-direction (two-side simultaneous cutting).

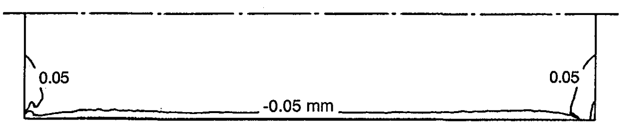


Fig.16 Distribution of maximum transient displacement in y-direction (two-side simultaneous cutting).

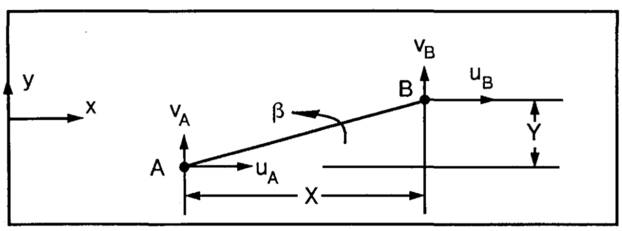


Fig.17 Rigid body rotation due to thermal deformation.

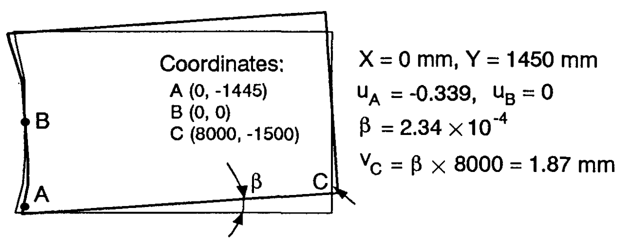


Fig.18 Displacement due to rigid body rotation.

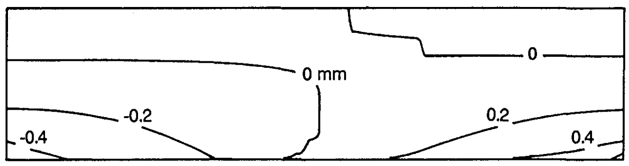


Fig.19 Distribution of maximum transient displacement in x-direction (one-side cutting).

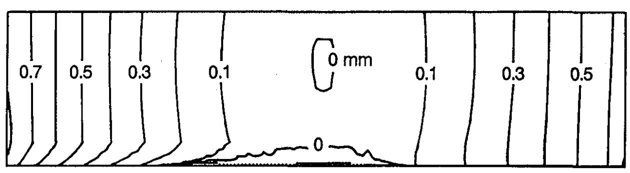


Fig.20 Distribution of maximum transient displacement in y-direction (one-side cutting).

increase of the ratio L/B, which means that a larger error arises in a long plate. It can be seen that the uncertainty of the constraint condition is a main factor in causing large variations in cutting error.

Figures 19 and **20** show the maximum transient displacements, as in Figs.15 and 16. Through comparison, it can be observed that much larger displacements in both x and y directions exist in widely extended area in the case of one-side cutting. Therefore, it is reasonable to say that rigid body motion has more influence on cutting precision in one-side cutting than in two-side simultaneous cutting.

5. Influence of Residual Stress

Because of high strength and good weldability, the TMCP steel plate produced by a controlled rolling and cooling process has been widely used in shipbuilding. However, water cooling causes a temperature gradient along the width of the plate, and residual stress occurs in the longitudinal direction. When residual stress exists, the cutting deformation, so-called camber, is often observed after a plate is longitudinally cut. Although the influences of different cooling processes on the residual stress have been examined [8)], the information on the magnitude and the distribution of residual stress in real plates is not available. Thus a distribution of residual stress with the maximum of 100 MPa is assumed in **Fig.21**. This residual stress is assumed to distribute uniformly along the longitudinal direction. The plate is considered 5000 mm in length, 2070 mm in width and 16 mm in thickness.

Numerical simulations are made for case C3 (simultaneous cutting along three lines: two are on two sides and one in the center of the plate) under the condition that residual stress exists in the plate. **Figure 22** shows the cutting error obtained from the thermal-elastic-plastic FEM computation. In the same figure, the cutting error produced by mechanical machine cutting (ideal cutting free from thermal deformation) is also shown for comparison. A small difference in cutting error is observed between flame cutting and mechanical cutting. It can be concluded that the influence of thermal deformation is relatively small and most cutting error is caused by residual stress.

For two-side simultaneous cutting with residual stress in the plate (case C4), simulation has also been carried out. **Figure 23** shows the results. The cutting error is very similar to that case C1 with no residual stress, as shown in Fig.10. Because the residual stress is symmetrically relaxed, the influence of residual stress on cutting error is very small in this case.

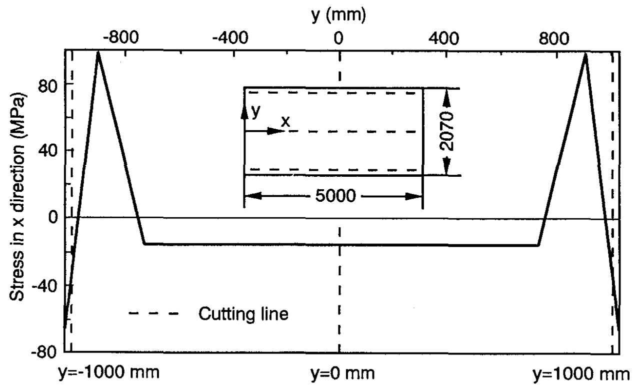


Fig.21 Assumed residual stress in steel plate.

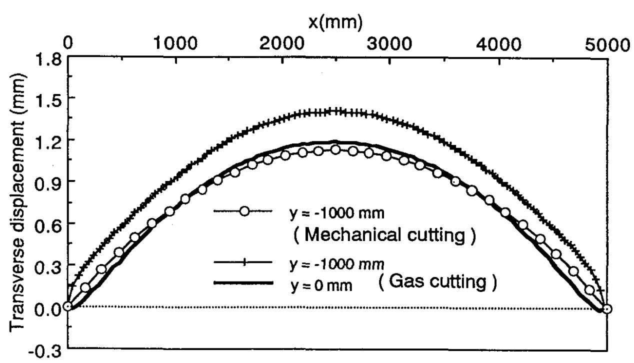


Fig.22 Effect of residual stress on cutting error (simultaneous cuttings along three lines).

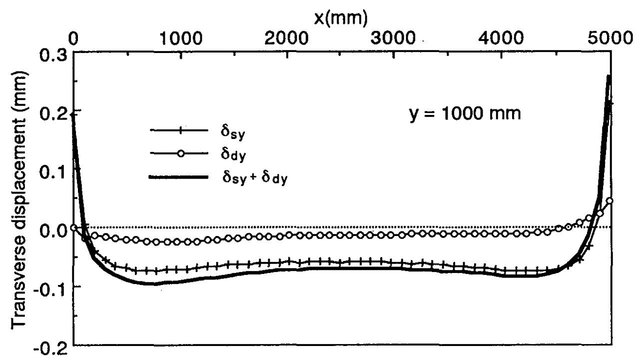


Fig.23 Effect of residual stress on cutting error (two-side simultaneous cutting).

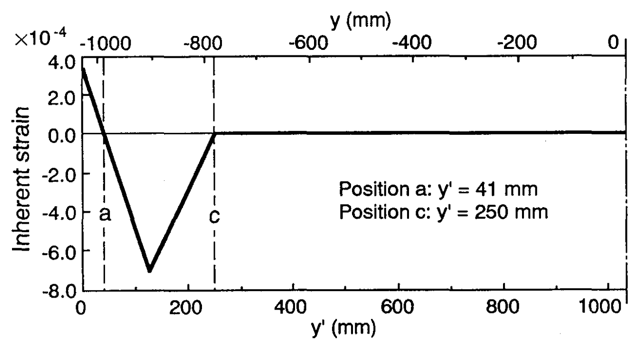


Fig.24 Distribution of inherent strain.

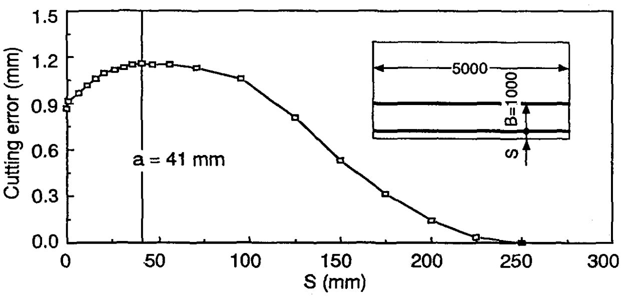


Fig.25 Effect of residual stress on cutting error (with fixed cutting width).

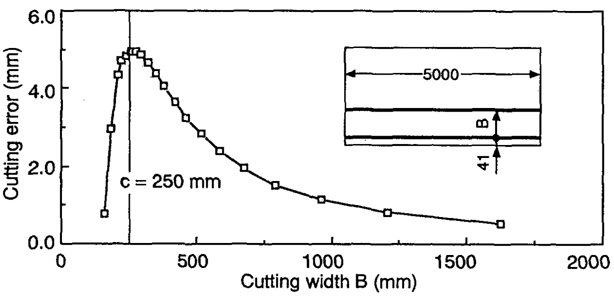


Fig.26 Effect of residual stress on cutting error (with fixed trimming width).

Distribution and magnitude are the basic factors used to measure the influence of residual stress on cutting error. At the same time, the relative position of the cutting line to the residual stress can be another important factor that affects cutting error. Thus, the influence of the cutting position is examined using FEM. Residual stress is relaxed after the plate is cut whereas the inherent strain, which is the source of the residual stress, remains unchanged. It is more convenient to use the inherent strain for this study. The inherent strain shown in **Fig.24** is obtained from the residual stress shown in Fig.21 by solving the inverse problem. The following two cases are used to examine the influence of cutting position by elastic FEM computation. The simulation can be considered ideal mechanical cutting.

The first case keeps the cut width B fixed at 1000 mm and changes the trimmed width S from 0 mm to 250 mm. The relation of cutting error (the amount of camber at the middle of the plate after the cut) to the trimmed width S is shown in **Fig.25**. The cutting error increases as the zone of positive inherent strain shown in Fig.24 is cut off, and the maximum is reached when the positive area of inherent strain is totally cut off. In the second case, the trimmed width S is kept at 41 mm and the cut width B is changed. As shown in **Fig.26**, the cutting error reaches its maximum (about 5 mm) when the B is equal to the width of the area where inherent strain exists.

Residual stress is assumed to be uniform in a longitudinal direction in this example. However, the distribution of residual stress is much more complicated in a real situation, and the problem becomes more complicated when the effects of cutting position and cut shape are considered. Therefore, residual stress can be considered another important factor that causes variations or scatter in cutting error.

6. Concluding Remarks

In this paper, influences of the factors related to thermal deformation and residual stress on the precision of flame cutting are investigated using FEM analysis. The thermal deformation is classified into two types: one is δ_s caused by residual plastic strain, and the other is caused by transient thermal deformation. Further, the transient thermal deformation can be separated into two parts. One is the error δ_d induced by the deviation of the position of the torch from the planed cutting line due to local thermal deformation. Another error δ_m is caused by the rigid body motion of the plate during cutting. One-side cutting and two-side simultaneous cutting are the basic models used for this study. The main conclusions drawn are as follows:

(1) In two-side simultaneous cutting, cutting errors δ_{sy} and δ_{dy} are so small that their effects can be ignored. At the same time, since the transient displacements are very small, the influence of the rigid body motion is also expected to be small.

(2) In one-side cutting, both errors δ_{sy} and δ_{dy} are large and become important causes of cutting error. Moreover, the error δ_m due to the rigid body motion can be large because the transient thermal displacements are large.

(3) Since the surface of the supporting table is usually uneven, the constraint condition becomes uncertain. The constraint condition also depends on the transient thermal deformation which changes with the torch position. The plate motion caused by this kind of constraint condition is an important factor which produces large variations or scatter in cutting error.

(4) Although figures on the distribution and magnitude of residual stress in steel plates are not thoroughly understood, the influence of residual stress on cutting precision is examined using an idealized distribution. When the maximum value of residual stress is 100 MPa, its effect becomes significantly large. In general, the error caused by residual stress is basically governed by the magnitude and gradient of the distribution. Its effect also varies with the cutting position and cut shape. Thus residual stress is another factor that causes variations in cutting error.

Acknowledgements

This research has been supported in part by the Ministry of Education, Japan. The authors are very grateful to Mr. Ryoichi KOKI (technical assistant of Welding Research Institute, Osaka University) and Mr. Terukazu TOKI (graduate student, Department of Mechanical Engineering, Doshisha University) for their help in conducting experiments for plasma cutting.

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