Study on the Influence of the Preheating Flame Characteristics and the Oxy-fuel Gas Cutting Performance

by Cesar Pinzon*, Student Member Naoki Osawa*, Member Yuichi Ikegami**, Member

Summary

To study the influence of the CO₂ on the cutting performance, the heat input due to preheating flame \( q_G \), and that due to the combustion of the material being cut \( q_B \) are estimated by performing a three-dimensional nonlinear heat conduction analysis that considers the temperature dependence of the thermomechanical properties. Spot heating tests are performed to identify the heat input parameters of the preheating gases H₂ and H₂-CO₂. Gas cutting tests are performed to identify the characteristics of the cutting groove shape while employing the selected preheating gases. Based on the information of the spot heating, and the gas cutting tests, a three-dimensional heat conduction analysis is performed to identify the temperature fields along the thickness direction of the workpiece. A new technique for the estimation of the temperature fields considering inclined cutting-fronts based on Matsuyama’s theory is proposed. The role of the preheating heat input and the material combustion heat input for the selected gases is examined. Based on the simulation results of this study, CO₂ deterioration mechanism on the cutting performance is discussed. From the study, the following results were obtained: (1) A new procedure for the kerf temperature estimation throughout the plate thickness based on the two-dimensional analysis of Matsuyama is established. The procedure allows a smooth and continuous temperature distribution through the plate thickness direction. (2) By applying the proposed procedure, it is possible to estimate the three-dimensional kerf temperature distribution on thick plates and allows the consideration of inclined cutting fronts. (3) By evaluating the preheating, and the material combustion heat input, it is observed a substantial declined in \( q_G \) when employing CO₂ while \( q_B \) remains unchanged regardless of the employed preheating gas.

1. Nomenclature

\( K_n \) Modified Bessel function of the n-th order.
\( R_0 \) Distance from the nozzle center to the spouts of preheating.
\( R_E \) Distance from the nozzle center to the end of the analysis region.
\( S_1, S_2, S_3 \) Boundaries at the cutting groove.
\( T_{2D}(s) \) Matsuyama’s two-dimensional temperature distribution at distance \( s \) from F.
\( T_{3D}(s) \) Temperature calculated by the 3D-FE analysis.
\( T_B \) Plate back face temperature.
\( T_G \) Gas temperature.
\( T_P \) Plate heating face temperature.
\( T_f \) Melting point temperature
\( k \) Heat conductivity of steel.
\( l_1, l_2 \) Length of \( S_1 \) and \( S_2 \) boundaries.
\( q_B \) Heat input due to material combustion.
\( q_G \) Heat input due to preheating gas.
\( q_{total} \) The sum of \( q_B \) and \( q_G \).
\( 3D-FE \) Three-dimensional finite element.
\( CO_2 \) Carbon dioxide

\( F \) Intersection point between the heating line center and the groove’s leading edge.
\( h \) Plate thickness.
\( H_2 \) Hydrogen
\( H_2O \) Water.
\( LPG \) Liquefied petroleum gas.
\( O_2 \) Oxygen
\( OHC \) Oxy-Hydrogen cutting.
\( x,y,z \) Fixed coordinate system
\( l \) Collocation point
\( v \) Cutting speed.
\( a \) Half kerf width.
\( d \) Kerf width.
\( q \) Heat flux.
\( r \) Distance from the nozzle center.
\( s \) Gauged path length along the groove from F.
\( \alpha \) Local heat transfer coefficient.
\( \kappa \) Cutting front lag.
\( \lambda \) Ratio of cutting front diameters in x and y directions.
\( \xi, \eta \) Moving coordinate system
\( \pi(x) \) Evaluation plane.

2. Introduction

During the Oxy-fuel cutting process, a workpiece is heated by a preheating flame until it reaches its kindling temperature, then oxygen is blown onto the workpiece which triggers an oxidation reaction of the steel that generates additional heat. During the process, two different sources of heat are supplied to the workpiece: first by the preheating flame hereafter referred as

* Osaka University
** Air Water Inc.

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"preheating heat input" and later by the oxidation of the steel hereafter referred as "material combustion heat input."

In recent years, there has been a growing interest in using H₂ for the preheating flame during the oxy-fuel cutting process since the use of H₂ improves the cutting performance, reduces the thermal distortion of the workpiece, and also reduces the CO₂ emissions during the process. In practical applications of OHC, the preheating flame is composed of a mixture of gases. Generally, H₂ is mixed with a fossil gas, such as LPG, to improve the visibility of the preheating flame since the H₂ flame is almost invisible, and the flame condition hard to adjust. Additionally, as reported by Taniguchi, by using a fossil gas helps to avoid drastic explosions during the mixture gas ignition, improving the process safety. However, one of the side effects of mixing fossil gases in the preheating flame is the reduction of cutting performance. Several studies have shown a deterioration of the cutting performance (e.g., cutting speed, kerf quality, thermal distortion) while adding fossil gases in the preheating flame. In this regard, the precise deterioration mechanism of the process has not been fully clarified yet. Another significant concern with the oxy-hydrogen preheating flame is that the flame optimization process is performed manually and usually relies on the individual skill of experienced workers. As a result, there is a considerable incentive to automate the preheating flame adjustment along with the gas composition optimization as much as possible.

In order to automate the preheating flame adjustment, clarification on the relationship of the preheating flame conditions and the cutting performance needs to be addressed. Osawa et al. developed a method to study the thermal effects during the piercing process. In their study, the distributions of the heat transfer parameters (Tₐ and α) were identified by performing an inverse heat conduction analysis of a thin circular plate during spot heating tests. This method was applied to analyze the piercing process employing the preheating flames H₂-LP and LPG. They reported that the local heat transfer efficiency of H₂-LP gas was significantly higher than that of LPG, and it leads to the superior performance of the OHC process.

When a fossil gas is mixed with H₂, the combustion of the preheating flame generates H₂O and CO₂ as byproducts. Ikegami studied the influence of CO₂ on the cutting performance by performing gas cutting tests of 50 mm thick plates using H₂ and a mixture of H₂-CO₂ gases. As a result, he reported that the cutting performance declined with the increase of CO₂ mixing ratio. Osawa et al. developed a finite element code to perform a three-dimensional heat conduction analysis in which the preheating and the cutting performance needs to be addressed. Osawa et al. proposed a direct identification technique for the preheating heat input and the material combustion heat input by performing gas cutting tests for the selected preheating gases. Three-dimensional finite element models are generated based on the measured groove geometry. During the heat conduction analysis, a new technique for the estimation of the temperature fields below the heating face is proposed. The kerf temperature distribution considering thick plates with inclined cutting-fronts is estimated by adopting the semi-analytical method proposed by Matsuyama. The ratio of the preheating heat input and the material combustion heat input is examined by performing a moving coordinate quasi-stationary finite element heat conduction analyses. Based on these simulation results, CO₂’s deterioration mechanism on the cutting performance is then discussed.

3. Theory

3.1 Preheating Heat Input

Osawa et al. proposed a hypothesis on heat transmission during line heating which assumes that the distribution of Tₐ, and α are time independent, therefore they only depend on the distance from the torch. This hypothesis is based on the measurement of gas temperature fields within the combustion flames during spot heating test, by using a laser induced fluorescence measurement system. This hypothesis can be represented in terms of a linear relationship between q and Tₐ as shown in Eq. (1).

\[ q(t;r) = -α(r)T_B(t;r) + α(r)T_a(r) \]  

Time histories of Tₐ are measured during a spot heating test, as shown in Fig. 1. Time histories of q and Tₐ can be estimated by an inverse heat conduction analysis from the measured Tₐ, Tₐ and α can be identified by a linear regression on the relation between q and Tₐ.

Osawa et al. proposed a direct identification technique for Tₐ and α based on genetic algorithms. The validity of this technique was demonstrated by comparing the identified Tₐ with the one measured by LIF. Osawa et al. showed that this technique can be applied to cases in which the temperature of the workpiece surface reached the ignition temperature.

3.1.1 Genetic representation of heat transfer parameters

A schematic view of the distribution of the heat transfer...
parameters over the region of analysis is presented in Fig. 2. The with \( 0 < r < R_o \) is called “inner region”, and that with \( R_o < r < R_e \) “outer region”.

In Osawa et al.’s analysis, in order to analyze the preheating during the oxy-fuel gas cutting, the following considerations were taken:

- \( T_G \) shows it maximum at \( r = R_o \), and the maximum \( T_G \) is close to the theoretical combustion temperature.
- \( T_G \) approaches the room temperature at \( r = \infty \).
- \( \alpha \) shows it maximum at \( r = R_o \).
- \( \alpha \) approaches the natural convection heat transfer coefficient when \( r = \infty \).

\[
T_G[r] = \begin{cases} 
\text{Min} & 0 < r < R_o \\
\text{Max} & R_o < r < R_e \\
\text{Close to theoretical combustion temperature} & r = R_e
\end{cases}
\]

\[
D = 10.00 \text{ mm} \\
R_0 = 2.75 \text{ mm} \\
R_e = 38.00 \text{ mm}
\]

Fig. 2 Representation of the heat transfer parameters distribution over the region of analysis. (a) Gas flame temperature and heat transfer coefficient distribution.
(b) Employed gas nozzle and the analysis region.

Based on these assumptions, \( T_G \) and \( \alpha \) are represented as follows:

a) Set the upper and lower bound of \( T_G \) and \( \alpha \) at \( r = 0 \), \( r_0 \), and \( r_e \): \( T_G_{\text{min}}, T_G_{\text{max}}, T_0, T_{\text{E,min}}, T_{\text{E,max}}, a_{\text{C,min}}, a_{\text{C,max}}, a_0, a_{\text{E,min}}, a_{\text{E,max}} \).

b) Give \( T_G \) and \( \alpha \) at \( r = 0, r = r_0, \) and \( r = r_e \) as:

\[
\begin{align*}
T_c &= T_{G_{\text{min}}} + d_1(T_{G_{\text{max}}} - T_{G_{\text{min}}}) \\
a_c &= a_{\text{C,min}} + e_1(a_{\text{C,max}} - a_{\text{C,min}}) \\
T_0 &= T_{0_{\text{min}}} + d_2(T_{0_{\text{max}}} - T_{0_{\text{min}}}) \\
a_0 &= a_{0_{\text{min}}} + e_2(a_{0_{\text{max}} - a_{0_{\text{min}}}}) \\
T_E &= T_{E_{\text{min}}} + d_3(T_{E_{\text{max}}} - T_{E_{\text{min}}}) \\
a_E &= a_{\text{E,min}} + e_3(a_{\text{E,max}} - a_{\text{E,min}})
\end{align*}
\]  

(2)

Where \( d_1, e_1, d_2, e_2, d_3, e_3 \) are real numbers ranging from 0 to 1.

c) Consider the case where a cutting torch with a fixed speed is aligned above a steel plate. Fixed coordinates \((x, y, z)\) are placed on the steel plate, with the \(xy\) plane in the steel plate plane.

The application range of Matsuyama et al.’s analysis is limited to two-dimensional linear problems. For that reason, these results cannot be directly applied to the analysis of oxy-fuel gas cutting where a temperature gradient in the through-thickness direction is generated due to the heat transmitted from the preheating flame. In the present study, Matsuyama’s method is modified so that the temperature dependency of the thermomechanical properties and the temperature gradient in the thickness direction can be taken into consideration.

### 3.2 Kerf Temperature Estimation

Matsuyama et al.\(^8\) developed a technique where the heat flux through the kerf is determined so that it is the same as the heat flux necessary for melting the metal to be cut at the cutting groove’s leading edge. Specifically, a quasi-stationary heat conduction field around the moving heat source is determined so that the temperature at the groove leading edge is kept at the melting point, and the adiabatic condition is fulfilled at the groove surface at the rear side of the torch.

Matsuyama et al.\(^8\) proposed to determine the coefficients of the two-dimensional quasi-stationary heat conduction field around a moving heat source so that they minimize the residual error between the temperature/thermal flux and the thermal boundary conditions at multiple evaluation points on the cutting groove. The boundary conditions of the cutting groove used in Matsuyama et al.’s analysis are shown in Fig. 3. At the leading edge (the Si boundary in Fig. 3) the temperature equals the melting point of the material. The kerf is assumed to be adiabatic and its well separated from the torch to the rear (the Si boundary in Fig. 3). The temperature and flux between S1 and S2 (the S1 boundary in Fig. 3) are calculated by using the determined coefficients.
3.4 Translation of the Temperature Field

In an analysis using the moving coordinates described in Section 3.3, the moving coordinate system \((\xi, \eta)\) in the plate and the fixed coordinate \(z\) in the plate thickness direction are combined to give the locations of the calculations points. In this analysis, the temperature field \(T_1(x, y, z)\) shows translational movement to the same extent as the torch displacement \((udt, vdt)\) in \(\Delta t\). Thus, the initial value of the time integration of the temperature at \((\xi - u\Delta t, \eta - v\Delta t, z)\) is given by the temperature at \((\xi - u\Delta t, \eta - v\Delta t, z)\) at \(t\). The detail of the time integration procedure is explained in Osaka et al.\(^7\).

3.5 Calculation of Kerf Temperature

3.5.1 Two-dimensional surface temperature field

Let \(\pi(x)\) be the plane parallel to the heating face with the thickness coordinate of \(z\). In the present study, the provisional temperature distribution on \(\pi(x)\) is given by the analytical method proposed by Matsuyama et al.\(^8\). In these calculations, the a tentative length of the \(S_3\) boundary (see Fig. 3) is given to all evaluation planes.

3.5.2 Three-dimensional temperature field

The workpiece’s three-dimensional temperature distribution during OHC process can be calculated by performing a three-dimensional finite element (3D-FE) moving coordinate quasi-stationary heat conduction analysis, with the heat flux of the preheating flame estimated in Section 3.1 and the provisional kerf temperatures given in Section 3.5.1.

The use of moving coordinates facilitates a finite element discretization which faithfully expresses the groove shape and also it prevents the accuracy deterioration in the heat input estimation caused by rapid changes in thermal boundary conditions, without the need for expressing the melting of the cut metal in terms of element death.

However, the provisional kerf temperatures given in Section 3.5.1 are calculated without the consideration of the temperature gradients along the thickness direction caused by the preheating flame, the temperature dependencies of the material properties are ignored, and the length of \(S_3\) boundary chosen in Section 3.5.1. is unrealistic. Apparently, the accuracy of the calculated three-dimensional temperature field is not expected. As described later, a sharp temperature discontinuity on the border between \(S_3\) (prescribed non-uniform temperature) and \(S_1\) (adiabatic boundaries) is calculated in the 3D-FE solution.

It is needed to adjust the kerf temperature on each \(\pi(x)\) in
order to reduce this temperature discontinuity, and achieve a heat conduction field which is consistent with the temperature gradient along the thickness direction due to the preheating flame, and the non-uniform thermal conditions for the groove leading edge and rear side of the kerf.

3.5.3 Three-dimensional temperature field adjustment
As shown in Fig.3, boundaries S1-S3 are set on each evaluation surface $\pi(x)$. During the gas cutting process, a temperature gradient along the thickness direction is caused by the preheating flame. Accordingly, the kerf temperature distribution on each $\pi(x)$ is modified by the following procedure, and they are adopted as the thermal boundary condition for the three-dimensional analyses. Because the temperature on S1 equals the melting point, and the temperature on S3 is adiabatic, temperature modification is only required on the S2 boundary. Let $T_{3D}(x)$ be the temperature calculated by the 3D-FE analysis in which $T_{2D}(x)$ is given as the S2 boundary condition.

Fig. 5 illustrates the kerf temperatures on the S2 and S3 boundaries. $\xi$ and $\eta$ are distances from the torch center measured in the cutting direction and the transversal direction. Osawa et al. reported that, when $\pi(x)$ is close to the heating face, $T_{2D}(x)$ becomes higher than $T_{2D}(x)$ on S2, and a sharp discontinuity arises on the S2/S3 border when the provisional kerf temperatures given in Section 3.5.1 are applied.

The S2 length ($l_1$ in Fig. 3) chosen in the provisional analysis is a tentative value, and it can be changed. Let $l_1 + \Delta l$ be the modified S2 length. $T_{2D}(x)$ is re-analyzed for this updated S2/S3 configuration. When this updated $T_{2D}(x)$ is applied in the 3D-FE analysis, the updated $T_{3D}(x)$ on S2 becomes higher than that before the updating, and the discontinuity becomes less significant (see Fig. 5). Adjusting $\Delta l$ on each $\pi(x)$ by trial and error, the optimized three-dimensional S2/S3 configuration, for which the temperature discontinuity on the S2/S3 border is negligible on all $\pi(x)$, can be determined.

4. Experimental Tests

4.1 Spot Heating Tests

4.1.1 Experimental setup
To identify the heat transient characteristics of the preheating flames, spot heating tests were performed. A mild steel circular plate of 300 mm diameter and 6 mm thickness was placed horizontally, and a preheating nozzle was positioned in the center of the plate with a standoff distance of 6 mm, as shown in Fig. 6. A set of thermocouples were placed at the back face to record the temperature distribution on the plate during the trials, and a heat insulation material was used to coat the back of the plate.

Two different sets of preheating flames were prepared for the trials. A 100% H2 (100%H2-0%CO2) and a gas mixture of 80% H2 and 20% CO2 (80%H2-20%CO2) are employed as the preheating flames. The preheating flame compositions employed during the trials are shown in Table 1.

Nissan Tanaka 3055B D5 No.4 LPG divergent nozzle[2], as shown in Fig. 2b, was used in all heating tests. This nozzle is suitable for cutting of steel plates up to 25 mm thick. The distance from the nozzle center to the preheating gas spouts, $R_0$, is 2.7 mm.

![Fig. 6 Test specimen used during the spot heating trials.](image)

The temperature distribution at the backface was measured using chromel-alumel thermocouples (Type-K) with a sheath diameter of 0.1 mm fitted in both perpendicular directions from the center. As shown in Fig. 7, the thermocouples were fitted using percussion welding. A pitch of 2 mm was used from the plate center up to 12 mm, then a 4 mm pitch was used from 12 mm up to 40 mm, and finally, a pitch of 8 mm was used on the periphery of the plate; 26 mm thick steel wool was attached to the back face. During the trials, the thermocouple output was recorded for 5 sec. at intervals of 0.2 sec. once the heating torch had been placed in the center of the plate. The movement of the torch was controlled by Daiden Fanuc ARC Mate DR-400 welding robot. The heating time for the tests was 6 sec., after that the torch was immediately removed from the plate so that the plate starts to cool down.

| Preheating Gas | 100%H2-0%CO2 | 80%H2-20%CO2 |
|----------------|--------------|--------------|
| Standoff distance [mm] | 6 | 6 |
| Pressure of H2 [MPa]  | 0.105 | 0.103 |
| Flow of H2 [l/min]  | 29 | 29 |
| Flow of Oxygen [l/min] | 6 | 6 |

![Table 1. Spot heating test heating conditions.](image)
4.1.2 Determination of heat transfer parameters

In this study, $T_G$ and $\alpha$ around the torch center were identified from the measured backface temperatures following the inverse heat conduction analysis method explained in Section 3.1.1. The comparison of the $T_G$ distributions for the chosen preheating flames is shown in Fig. 8. From the figure, it is observed that the 100%H$_2$-0%CO$_2$ flame, shows a higher temperature than the 80%H$_2$-20%CO$_2$ flame, especially at $R_0$.

The $\alpha$ distributions are presented in Fig. 9. It is observed that $\alpha$ shows its maximum at $R_0$. $\alpha$ of 80%H$_2$-20%CO$_2$ shows a significant decrease in the vicinity of the spout ($r < 2.7$ mm and $r > 2.7$ mm) compared to 100%H$_2$-0%CO$_2$.

To examine the accuracy of the identified parameters, the measured temperatures from the thermocouples located at a distance $r = 4, 6, 8, 10$ and 12 mm on the plate backface are calculated by direct finite element heat conduction analyses where the heat transfer parameters ($T_G$ and $\alpha$) presented in Figs. 8 and 9 are adopted. Fig. 10 shows the comparisons of the calculated and measured backface temperatures for the preheating flames: 100%H$_2$-0%CO$_2$ (Fig. 10a), and 80%H$_2$-20%CO$_2$ (Fig. 10b). In these figures, the calculated temperatures agree well with those measured in the experiments. This demonstrates the accuracy of the identified heat transfer parameters.
4.2 Cutting Tests

4.2.1 Experimental setup

Oxy-hydrogen gas cutting tests for thick steel plate was performed. For this test, two steel specimens with the dimensions presented in Fig. 11 were prepared. During the cutting tests, the first steel specimen was cut by employing the preheating flame 100%H2-0%CO2, and in the same manner, the second steel specimen was cut by employing the preheating flame 80%H2-20%CO2. Once the cutting process finished, the resulting geometry of the cut was measured for each specimen. The preheating gas flame conditions employed during the trials were the same as those used during the spot heating test shown in Table 1.

Fig. 11 shows the shape and size of the specimens. That is mild steel (SS400) rectangular plate with a length of 200 mm x width 100 mm x thickness 25 mm. The mill scale was not removed before cutting. Let x and y be the longitudinal and transversal coordinates on the plate. The origin is set at the model end on the center line. A 10 mm diameter hole was opened using a drill at the point with (x, y)=(25 mm, 0 mm). Heating is carried out along the x-axis, starting at the drill hole (x = 25 mm) and ending at x = 145 mm. During the trials, the specimens were not pierced before the cutting. \( V \) was set to 5 mm/sec for both preheating flames. For all the cutting trials performed in this study, the cut face quality met the best grade (Grade 1) of JWES WES2801 (quality standard for gas cut surface)\(^1\), and there was no dross adhesion.

Let ‘groove tip’ be the intersection between the cutting center line and the leading edge (point F in Fig. 3), and \( k \) be the distance in the x-direction between the groove tips on the front and back faces (see Fig. 11). Once the cutting process finished, d was measured, and then the specimen was cut along the centerline in order to measure the groove’s leading edge shape. On this cut surface, x-coordinates of groove tips on the front and backface were measured, and the cutting-front lag \( k \) was calculated.

Let \( (x, y) \) be the coordinates of the groove tips on the backface, and let \( (x_1, y_1) \) be the coordinates of the groove tips on the frontface. The cutting-front lag \( k \) is defined as the distance between the groove tips on the front and backfaces, and \( d \) is defined as the diameter of the preheating flame. The distance between the groove tips on the backface and the frontface is calculated using the following equation:

\[
\frac{x_1}{x_1} - \frac{x}{x} = k
\]

Fig. 11 Steel plate specimen used in cutting test.

4.2.2 Measurement results

The steel plate specimens employed during the cutting tests are shown in Fig. 12, and the measured shape parameters \((d, k, \lambda)\) are shown in Table 2. From the table can be observed that, for the selected cutting speed, there is no significant difference in the groove shape and size. However, a significant difference is observed in the cutting-front lag.

### Table 2. Summary of the gas cutting test results.

| Preheating Gas | 100%H2-0%CO2 | 80%H2-20%CO2 |
|----------------|--------------|--------------|
| Plate thickness \( h \) [mm] | 25 | 25 |
| Cutting speed \( V \) [mm/s] | 5 | 5 |
| Cutting-front lag \( k \) [mm] | 1 | 3.5 |
| Groove width \( d \) [mm] | 3 | 3 |
| Ratio of groove diameters \( \lambda \) | 1.0 | 1.0 |

Fig. 12. Steel plate specimen cutting groove. (a) 100%H2-0%CO2; (b) 80%H2-20%CO2

5. Numerical Calculation Results

5.1 Analysis of Gas Cutting Test

5.1.1 Implementation of moving coordinate system analysis

Osawa et al.\(^7\) developed an in-house three-dimensional finite element code MOVEFLUX that can perform a quasi-stationary heat conduction analysis employing the moving coordinates (Section 3.3) and the local heat transfer model for the preheating flame (Section 3.1). The heat transmitted to the workpiece from the preheating flame and the metallic combustion can be evaluated separately by using this code.

5.1.2 Model description

One-half finite element models shown in Figs. 14 and 15 are used during the finite element analyses. These models consist of 8 node isoparametric hexagonal elements. The heat flux from the preheating flame is calculated on the top face using the heat transfer parameters shown in Figs. 8 and 9. The convective heat transfer between the work and air is evaluated on the side and back faces, and its coefficient is 480 W/(m²K). Temperature-dependent material properties shown in Fig. 13 are used in analyses. The initial temperature is 300 K.
As shown in Table 2, it was observed that there was no significant difference in the in-plane groove’s edge shape between 100%H2-0%CO2 and 80%H2-20%CO2. The groove’s leading edge can be approximated as a semicircle with \( a = 1.5 \) mm. Therefore, the same in-plane one-half mesh is adopted for both cases, and the three-dimensional meshes are generated by extruding this in-plane mesh. For this in-plane mesh, fine quadrangle elements are arranged along the curved groove edge, and they are configured so that the mesh becomes sparser as the distance from \( F \) (Fig. 3) increases. The minimum element edge length is 0.236 mm along the edge, and 0.243 mm in the normal direction of the edge.

Table 2 shows that the cutting front lag \( \lambda \) was negligible for 100%H2-0%CO2 while it was about 14% of the plate thickness (25 mm) for 80%H2-20%CO2. Therefore, the extrusion is performed along the normal direction for 100%H2-0%CO2, and along the inclined direction for 80%H2-20%CO2 (Figs. 14 and 15). The element size is configured so that the edge length in thickness direction becomes larger with the distance from the front face. The minimum edge length in the thickness direction is 0.5 mm. The total number of nodes and elements are 67536 and 61893, respectively. Because of the inclined extrusion direction, the model end shows an inclined cross section for 80%H2-20%CO2. However, this does not affect the accuracy of the temperature calculation because the uniform room temperature is given to the nodes on this section during the time integration of the heat conduction analysis when the temperature is updated.

5.1.3 Provisional Kerf Temperature Calculation
Once the groove’s geometry (\( a \) and \( \lambda \)) and the torch speed \( V \) are given, \( T_{2D}(s) \) in Section 3.5.3 can be calculated by Matsuyama’s method8 as

\[
\tilde{T}_I = \exp\left(-\mu_I \cos(\phi_I)\right) \sum_{n=0}^{N-1} c_n K_n \cos((I-1)\phi_I); \quad (6)
\]

\[
\tilde{T}_I = T/T_f
\]

Where,

\[
C_n = \left( (A_{in})^T(A_{in}) \right)^{-1}(A_{in})^T(B_I)
\]

\[
A_{in} = \begin{cases} 
K_n(\mu_I) - \cos \left( \frac{\pi}{2} \right) \cos(\pi \phi_I) - \frac{1}{\pi} \sin \left( \frac{\pi}{2} - \phi_I \right) & (1 \leq I \leq L) \\
K_n(\mu_I) - \cos \left( \frac{\pi}{2} \right) \cos(\pi \phi_I) & (L+1 \leq I \leq L+M)
\end{cases}
\]

\[
B_I = \begin{cases} 
1.0 & (1 \leq I \leq L) \\
0.0 & (L+1 \leq I \leq L+M)
\end{cases}
\]

Fig. 14 Finite element mesh used for 100%H2-0%CO2 heat conduction analysis. (a) top view (b) side view.

Fig. 15 Finite element mesh used for 80%H2-20%CO2 heat conduction analysis. (a) top view (b) side view (c) enlarged view of the cutting groove.
In Eqs. (6) and (7), \( \mu_i = V r_i / 2 k \), \( r \) and \( \phi \) are defined in Fig. 3. L and M are the numbers of collocation points on the S1 and S2 boundaries respectively. In the same manner as Osawa et al.\(^7\), parameters shown below are adopted.

1. The groove leading edge is approximated as semicircle with \( a = 1.5 \) mm and \( y = \phi \). \( T_f \) is set to 1800 K\(^6\).
2. The S1 boundary starts at point F (Fig. 3) and ends at the point right beside the torch center (point M in Fig. 3). The length of S1 and S2 boundaries \( l_1 \) and \( l_2 \), are 0.5\( a \) and 1.1\( a \). \( l_i \) is altered in the following iterative analyses.
3. S1 is divided into 15 equal sections, S2 into 7 equal sections and S3 in to 15 equal sections and the collocation points are arranged at the section division points.

The calculated \( T_{2D} \) along the solidification line is shown in Fig. 16. This temperature distribution is given to the finite element nodes on the kerf as the provisional temperatures for the three-dimensional analyses.

Fig. 16 Change of the kerf temperature along the solidification line.

### 5.1.4 Three dimensional kerf temperature distribution

The three-dimensional temperature distribution on the cutting groove is calculated by MOVEFLUX adopting the provisional two-dimensional kerf temperature (\( T_{2D} \)) to each evaluation plane. This result is called ‘provisional solution’. For the 100%H\(_2\)-0%CO\(_2\) model, the provisional solution's three-dimensional quasi-stationary temperature field is shown in Fig. 17, and the kerf temperature distribution on the heating face is shown in Fig. 18. As expected in Section 3.5.2, a sharp temperature discontinuity is observed in the vicinity of the S2/S3 border. Fig. 18 shows that \( T_{3D} \) on the S1 boundary is higher than \( T_{2D} \). This is due to the heat supply from the preheating flame (Osawa et al.\(^7\)).

As discussed in Section 3.5.3, this discontinuity can be overcome by adjusting the length of S2 boundary \( l_i \) on each evaluation plane \( \pi(z) \). The S2 temperature near the S2/S3 border can be raised by increasing \( l_i \), while it can be decreased by reducing \( l_i \). This adjustment is performed iteratively so that \( T_{3D} \) becomes close to \( T_{2D} \) at the border on every \( \pi(z) \), by repeating the process, a smooth and continuous temperature distribution along both the solidification line and the thickness direction is achieved.

![Fig. 17 Temperature discontinuities generated during the 100%H\(_2\)-0%CO\(_2\) three-dimensional heat conduction analysis.](image)

![Fig. 18. Comparison of kerf temperatures on the heating face obtained by Matsuyama’s two-dimensional solution and that from the three-dimensional analyses.](image)

For the 100%H\(_2\)-0%CO\(_2\) model, the temperature field without discontinuity and the smooth kerf temperature distribution along the solidification line and the thickness direction, which are derived from the adjusted kerf temperature on each plane, are shown in Figs. 19 and 20. These results demonstrate that the kerf temperature adjustment technique proposed in Section 3.5.3, is effective for the analysis of thicker plates (25 mm-thick) considering non-inclined straight leading edge. Fig. 21 shows the calculated heating face temperature distribution for 100%H\(_2\)-0%CO\(_2\) at \( V = 5 \) mm/sec. by implementing the proposed technique. The result shows the smooth and continuous temperature distribution in the heating face during the analysis.
The proposed kerf temperature adjustment technique is applied to the 80%H₂-20%CO₂ model, which shows an inclined cutting-front. The adjusted temperature field without discontinuity is shown in Fig. 22, and the smooth groove temperature distribution along the solidification line and the thickness direction are shown in Fig. 23. In the same manner as the 100%H₂-0%CO₂ model, a
smooth and continuous temperature distribution along both the solidification line and the thickness direction is achieved. This means that the proposed technique can be also applied to thicker plates with inclined cutting-front.

6. Cutting Performance Analysis

The heat input from preheating gas, $q_G$, can be calculated by integrating the heat flux due to preheating heat transfer. The heat flux on the kerf can be estimated from the temperature gradient in the element adjacent to the kerf. The heat input due to material combustion (self-burning), $q_B$, is calculated by integrating the heat flux on the kerf. Let $q_{\text{total}}$ be the sum of $q_G$ and $q_B$. The heat inputs per unit time for both models are calculated.

Table 3 and Figure 24 shows the calculated $q_G$, $q_B$, and $q_{\text{total}}$ for the preheating flames 100%H2-0%CO2, and 80%H2-20%CO2. The table and figure show that $q_G$ per unit time of 100%H2-0%CO2 is about 43% larger than that of 80%H2-20%CO2, while the difference in $q_B$ is small (about 0.97%).

| Preheating gas       | Cutting speed [mm/s] | Heat flux per unit time $q_G$ [J/s] | Heat flux per unit time $q_B$ [J/s] | Total $q_{\text{total}}$ [J/s] |
|----------------------|----------------------|-----------------------------------|-----------------------------------|-----------------------------|
| 100%H2-0%CO2         | 5                    | 2299                              | 2542                              | 4841                        |
| 80%H2-20%CO2         | 5                    | 1606                              | 2567                              | 4173                        |

Table 3. Heat flux per unit time.

![Heat flux per unit time](image)

Fig. 24 Heat input from the preheating gas flame and that from the material combustion.

Table 1 shows that the amount of burning gas (H2) and the oxidizing agent (O2) supplied in the 80%H2-20%CO2 preheating flame is the same as that for the 100%H2-0%CO2 preheating flame. The results of Table 3 and Fig. 24 show that the heat transfer from the preheating flame significantly decreases when CO2 is mixed into H2, while the heat efficiency of material combustion is hardly affected by the presence of CO2 when the same amount of O2 is supplied.

Ikegami[6] reported that the cutting performance of Oxy-Hydrogen cutting deteriorates when CO2 is mixed into the preheating gas, and he supposed that this deterioration was due to the decline in the heat efficiency of material combustion. However, the results obtained in this study suggest that the cutting performance deterioration by the presence of CO2 observed in Ikegami’s experiment was caused solely by the decrease in the heat transfer from the preheating flame.

7. Conclusions

To study the influence of the CO2 on the cutting performance heat input due to preheating flame $q_G$, and that due to the combustion of the material being cut $q_B$ are studied by performing a three-dimensional non-linear heat conduction analysis, that considers the temperature dependences of the thermomechanical properties. Spot heating tests are performed to identify the heat input parameters of the preheating gases H2 and H2-CO2. Gas cutting tests are performed to identify the characteristics of the cutting groove geometry while employing the selected preheating gases. Based on the information of the spot heating, and the gas cutting tests, a three-dimensional heat conduction analysis developed by Osawa et al.[7] is performed to identify the temperature fields along the thickness direction of the workpiece. A new technique for the temperature fields estimation along the thickness direction considering inclined cutting-fronts based on Matsuyama’s method[8] is proposed. The role of the preheating heat input and the material combustion heat input on the cutting performance for the selected gases is then examined. From the study, the following results were obtained:

1. A new procedure for the kerf temperature estimation throughout the plate thickness based on the two-dimensional analysis of Matsuyama et al.[8] is established. The procedure allows a smooth and continuous temperature distribution through the plate thickness direction by the iterative adjustment of the S2 boundary length on each evaluation plane.

2. By applying the proposed procedure, it is possible to estimate the three-dimensional kerf temperature distribution on thick plates and also allows the consideration of inclined cutting fronts during the analysis.

3. By evaluating the preheating, and the material combustion heat input, it is observed a substantial declined in $q_G$ while employing 80%H2-20%CO2 preheating flame whereas, $q_B$ remains unchanged regardless of the employed preheating flame. The results obtained in this study suggest that the cutting performance deterioration reported by Ikegami[6] was caused solely by the decrease in the heat transfer from the preheating flame.

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