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# Quantification of shrinkage deformation on line-heating

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## Abstract

The bending processing of a ship Hull is carried out by Line-Heating using gas heating generally. This Line-Heating technique is based on the experience and the feeling of the skilled workers. This tacit knowledge is difficult to hand down and educate the skill to the new workers efficiently. Therefore, the quantification of this Line-Heating technique is expected to make learning the skill easy. Moreover, the quantification analysis of Line-Heating is indispensable for the systemizing and computerizing of ship building processing to increase further productivity. Therefore, much research about the quantification analysis of Line-Heating was carried out in the nineteen-nineties. However, the accuracy of the deformation estimation is insufficient because the past research was focused only on angular distortion. On Line-Heating, not only angular distortion but also shrinkage deformation is important. However, the data of shrinkage deformation is insufficient. Therefore, in this study, Line-Heating fundamental experiment using two type gases (acetylene and propane) was carried out to create the shrinkage deformation database. Heating velocity, gas flow rate and thickness of the plate were set parameter. 72 conditions data were obtained. The quantification relations between amount of heat input and quantity of angular distortion, quantity of transverse shrinkage or force of longitudinal shrinkage were determined. From the experimental results, it is clear that quantity of transverse shrinkage and force of longitudinal shrinkage are expressed by the following unified equation unrelated to gas species. $F_t = D_tTE = 200Q$. Here, $F_t$ is force of longitudinal shrinkage, $D_t$ is quantity of transverse shrinkage, $T$ is thickness of plate, $E$ is Young's modulus and $Q$ is heat input. This equation is similar to the White's equation used in welding researches. Additionally, the confirmed experiment was carried out to verify the accuracy of this equation.

# 1 Heat input parameter

Quantity of heat input per unit length $Q$ (J/m) is decided by movement velocity of gas touch $v$ (m/s) and quantity of combustion heat per unit time $q$ (J/s) calculated from combustion gas flow rate.

$$Q = q/v \tag{1}$$

On Line-Heating, angular distortion $\Theta$, transverse shrinkage $D_t$ and longitudinal shrinkage $D_l$ are generated. From the theory of welding deformation [1], following equations seem to be available [2].

$$\Theta = F_n(Q/T^2) \tag{2}$$

$$D_t = \alpha_1 Q/TE \tag{3}$$

$$\int D_l db = \alpha_2 Q(L/BTE) \tag{4}$$

Here, $T$ is plate thickness, $F_n(*)$ is the function of *, $\alpha_1$ and $\alpha_2$ are constant, $L$ and $B$ are length and width of plate respectively and $E$ is Young's modulus. Eqn (4) is the integral calculus of longitudinal shrinkage $D_l$ in the direction to plate width on the section between the referential parallel lines whose interval is $L$. This equation is rewritten as following eqn (5) for evaluating force of longitudinal shrinkage $F_t$.

$$F_t = \alpha_2 Q = BTE\int D_l / L db \tag{5}$$

Constant $\alpha_1$ and $\alpha_2$ in eqns (3), (4) and (5) are dimensionless because the dimension of $Q$ is J/m = N.

On this research, the relations between quantity of heat input $Q$ (J/m) and angular distortion $\Theta$ (rad.), quantity of transverse shrinkage $D_t$ (mm) or force of longitudinal shrinkage $F_t$ (N) will be investigated experimentally.

# 2 Experimental methods

## 2.1 Materials

Four types of thickness (10, 16, 19 and 22mm) of polished steel were used for test materials. The chemical composition and the mechanical properties are shown in table 1.

## 2.2 Measurement method

The configuration of test specimens and the measurement points are shown in figure 1. Twenty-one lines in direction to longitudinal and nineteen lines in direction to transverse were scribed on the both side surfaces of test specimens. Three coordinates X, Y and Z at each cross point of scribed lines were measured before and after Line-heating by measurement equipment whose official accuracy is 1/100mm. The X and Y axis of coordinates on the surface of test specimens were on the basis of the origin that is located on the one of outermost cross points of scribed lines (refer to figure 1).

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Table 1: The chemical composition and the mechanical properties

| | | Chemical Composition (%) | | | | | Mechanical Properties | | |
|---|---|---|---|---|---|---|---|---|---|
| Type | Thickness | C | Si | Mn | P | S | Yield Strength | Tensile Strength | Elon-gation |
| | mm | ×100 | | | ×1000 | | MPa | MPa | % |
| SS400 | 10 | 16 | 2 | 41 | 13 | 7 | 348 | 477 | 30 |
| SS400 | 16 | 18 | 18 | 52 | 15 | 13 | 302 | 448 | 30 |
| SS400 | 19 | 9 | 23 | 65 | 14 | 19 | 284 | 417 | 32 |
| SS400 | 22 | 19 | 16 | 52 | 23 | 12 | 282 | 446 | 24 |

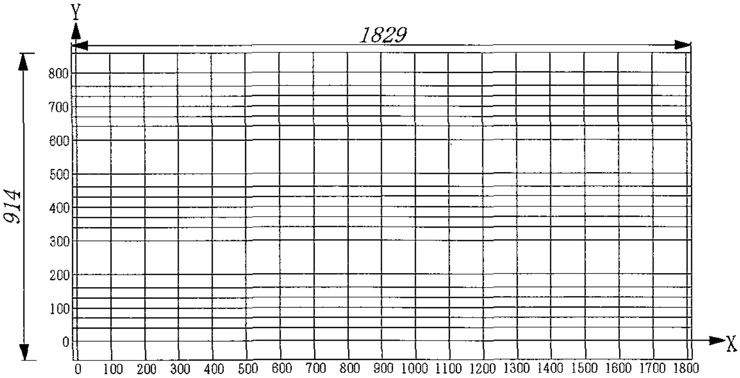


Figure 1: The configuration of test specimens and the measurement points

## 2.3 Heating method

The heat source of Line-Heating is mainly acetylene or propane. In this study, these two type gases were used on the experiments.

### 2.3.1 Fundamental experiment

Line-Heating was carried out using three types of gas touch nozzle and three conditions of touch movement velocity on each types of plate thickness and on each gas types as shown in table 2. Single nozzle of gas touch was used on each test specimens. Line-Heating was carried out on the three positions Y = 100mm, 400mm and 700mm in figure 1 under the condition of the movement velocity of gas touch 800mm/min, 600mm/min and 400mm/min respectively. Moreover, on calculating theoretical heat input to plate by theoretical calorific value, heat efficiency $\eta$ given by the following equations was considered [3]. Here, $v$ is movement velocity of gas touch (mm/s) and $T$ is thickness of test plate (mm). After this, quantity of heat input in this paper is set to the value calculated by multiplying calorific value and this efficiency.

Table 2: Heating conditions of fundamental experiment

| Gas Type | Gas Touch Number | Velocity | Calorific Value | Theoretical Heat Input, kJ/m | | | |
|---|---|---|---|---|---|---|---|
| | | mm/min | kJ/m | T=10mm | T=16mm | T=19mm | T=22mm |
| Acetylene | #1200 | 800 | 1330 | 582 | 643 | 674 | 705 |
| | | 600 | 1773 | 741 | 803 | 834 | 865 |
| | | 400 | 2660 | 1060 | 1122 | 1153 | 1184 |
| | #2500 | 800 | 2771 | 1212 | 1340 | 1405 | 1469 |
| | | 600 | 3695 | 1544 | 1673 | 1737 | 1801 |
| | | 400 | 5542 | 2209 | 2338 | 2402 | 2466 |
| | #4000 | 800 | 4433 | 1939 | 2145 | 2247 | 2350 |
| | | 600 | 5911 | 2471 | 2677 | 2779 | 2882 |
| | | 400 | 8867 | 3535 | 3741 | 3843 | 3946 |
| Propane | L1000 | 800 | 1802 | 595 | 595 | 595 | 595 |
| | | 600 | 2403 | 793 | 793 | 793 | 793 |
| | | 400 | 3604 | 1189 | 1189 | 1189 | 1189 |
| | L3000 | 800 | 5406 | 1784 | 1784 | 1784 | 1784 |
| | | 600 | 7208 | 2379 | 2379 | 2379 | 2379 |
| | | 400 | 10813 | 3568 | 3568 | 3568 | 3568 |
| | L5000 | 800 | 9011 | 2973 | 2973 | 2973 | 2973 |
| | | 600 | 12014 | 3965 | 3965 | 3965 | 3965 |
| | | 400 | 18021 | 5947 | 5947 | 5947 | 5947 |

Table 3: Heating conditions of accuracy confirmation experiment

| Specimen Number | Gas flow Rate | Velocity | Heat Input | Specimen Number | Gas flow Rate | Velocity | Heat Input |
|---|---|---|---|---|---|---|---|
| acetylene | l/h | mm/min | kJ/m | propane | l/h | mm/min | kJ/m |
| 10-1 | 1600 | 445 | 1285 | 10-3 | 1250 | 400 | 1105 |
| 16-1 | 3750 | 445 | 3011 | 16-4 | 3200 | 400 | 2828 |
| 19-1 | 4500 | 315 | 4946 | 19-4 | 3500 | 330 | 3686 |
| 22-1 | 3300 | 230 | 4863 | 22-2 | 3600 | 250 | 4905 |
| 10-2 | 2100 | 640 | 1227 | 10-5 | 2150 | 700 | 1165 |
| 16-2 | 3700 | 445 | 2971 | 16-5 | 3750 | 400 | 3314 |
| 19-2 | 3900 | 335 | 4050 | 19-3 | 4050 | 370 | 3841 |
| 22-4 | 4000 | 240 | 5663 | 22-5 | 3800 | 260 | 4991 |
| 10-4 | 2850 | 900 | 1255 | 10-6 | 2700 | 900 | 1189 |
| 16-3 | 3750 | 445 | 3011 | 16-6 | 3250 | 400 | 2872 |
| 19-5 | 4150 | 355 | 4087 | 19-6 | 4300 | 390 | 3888 |
| 22-3 | 4000 | 250 | 5450 | 22-6 | 4250 | 270 | 5389 |

$$\eta = 0.00058vT + 0.36 \text{ (acetylene)} \quad (6)$$
$$\eta = 0.33 \quad \text{(propane)} \quad (7)$$

On heating, the tip of gas touch corn was positioned at the surface of plate. The gas touch was moved using an electrically driven cart. The moving velocity was calibrated and adjusted.

#### 2.3.2 Accuracy confirmation experiment

On the basis of experimental equation of angular distortion obtained from fundamental experiment, heating conditions processing cylinder whose curvature radius is about $R$ = 2000mm were calculated. For accuracy confirmation by comparing this estimated curvature radius and real that after heating, Line-Heating was carried out on these conditions as shown in table 3. Nine positions between Y = 0mm and Y = 800mm on each test specimens are heated on these conditions in direction to X coordinate at 100mm interval (refer to figure 1).

## 3 Results and discussion

### 3.1 Results of fundamental experiment

#### 3.1.1 Angular distortion

The relation between angular distortion $\Theta$ and heat input parameter $Q/T^2$ is shown in figures 2 and 3. Each figure shows the result of acetylene and the results of propane respectively. The results of 10mm thickness where distorted buckling is generated are shown by white-painted square and the results of others are shown by black-painted circle. In case that $Q/T^2$ is higher than about 20(kJ/m)/mm$^2$, steel plate buckled and there is little angular distortion. The mechanism of angular distortion is classified into following two groups by the value of $Q/T^2$.

1) $Q/T^2$ is less than 10(kJ/m)/mm$^2$: Angular distortion is increasing with increasing of $Q/T^2$. This range seems to be the suitable condition for bending processing by Line-Heating. The relation between angular distortion $\Theta$ and heat input parameter $Q/T^2$ is approximately given by the following experimental equations.

$$\Theta = 22.7\text{Ln}(Q/T^2)\text{-}9.0 \text{ (acetylene)} \quad (8)$$
$$\Theta = 24.5\text{Ln}(Q/T^2)\text{-}3.2 \text{ (propane)} \quad (9)$$

2) $Q/T^2$ is more than 10(kJ/m)/mm$^2$:

Acetylene: Though distorted buckling with saddle shape deformation is slightly generated, angular distortion is increasing with increasing of $Q/T^2$.

Propane: There is little angular distortion even if $Q/T^2$ is increasing. This range seems to be the suitable condition for shrinkage processing without bending.

#### 3.1.2 Force of longitudinal shrinkage

The relation between force of longitudinal shrinkage $F_t$ and quantity of heat input $Q$ is shown in figures 4 and 5. Each figure shows the result of acetylene and the results of propane respectively. The results of 10mm thickness where distorted buckling is generated are shown by white-painted square and the results

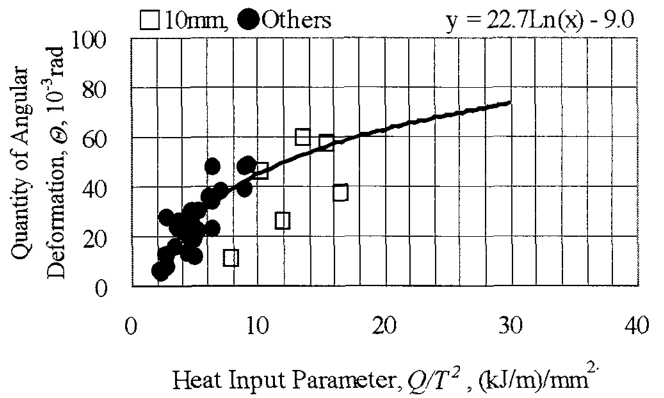


Figure 2: Relation between quantity of angular distortion and heat input parameter (acetylene)

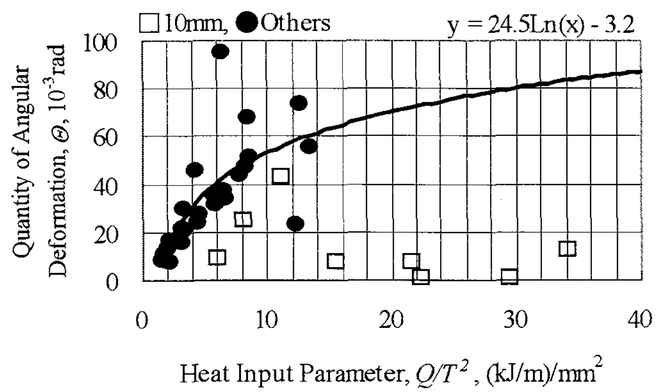


Figure 3: Relation between quantity of angular distortion and heat input parameter (propane)

of others are shown by black-painted circle. In case of acetylene, the relation between force of longitudinal shrinkage $F_t$ and quantity of heat input $Q$ has a good proportional relationship except test specimens with distorted buckling. On the test specimens with distorted buckling, it seems that the real girth length is different from the measurement value that obtained on measurement points at 100mm interval because the complex deformation in direction to outside of surface was generated. In case of propane, the relation between force of longitudinal shrinkage $F_t$ and quantity of heat input $Q$ has a proportional

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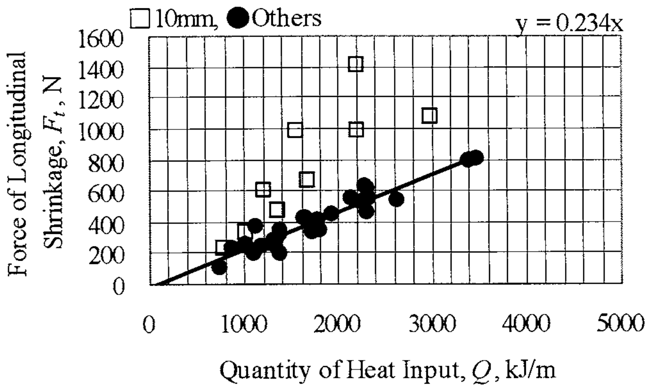


Figure 4: Relation between force of longitudinal shrinkage and quantity of heat input (acetylene)

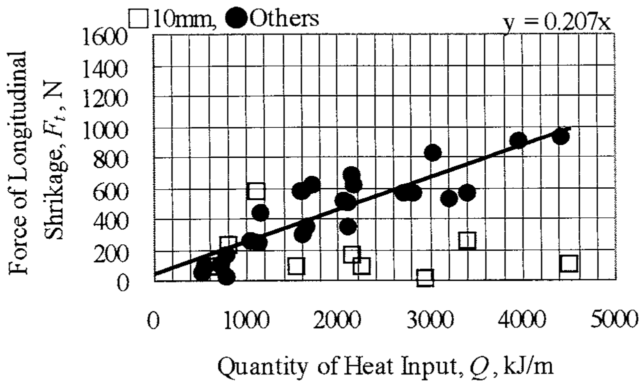


Figure 5: Relation between force of longitudinal shrinkage and quantity of heat input (propane)

relationship including slightly scattering except test specimens with distorted buckling. Calculating $\alpha_2$ in eqns (4) and (5) from figures 4 and 5, the relation between force of longitudinal shrinkage $F_t$ and quantity of heat input $Q$ is approximately given by the following experimental equations.

$$F_t \text{ (N)} = 0.234Q \text{ (kJ/m) (acetylene)} \quad (10)$$

$$F_t \text{ (N)} = 0.207Q \text{ (kJ/m) (propane)} \quad (11)$$

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### 3.1.3 Quantity of transverse shrinkage

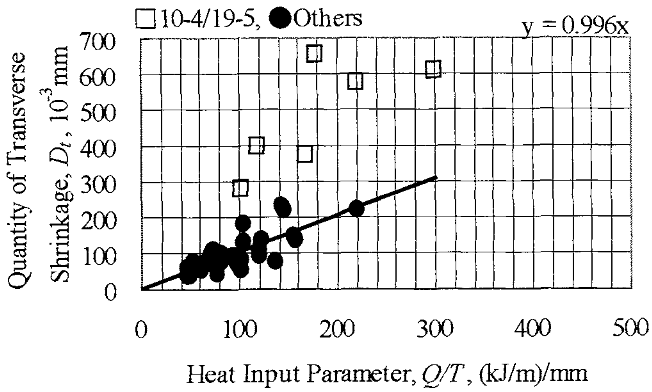


Figure 6: Relation between quantity of transverse shrinkage and heat input parameter (acetylene)

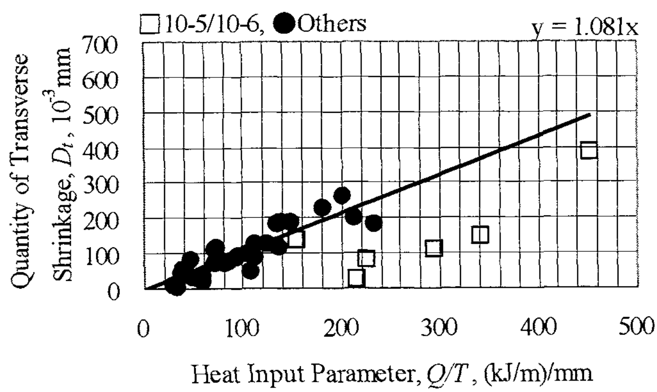


Figure 7: Relation between quantity of transverse shrinkage and heat input parameter (propane)

The relation between quantity of transverse shrinkage $D_t$ and heat input parameter $Q/T$ is shown in figures 6 and 7. Each figure shows the result of acetylene and the results of propane respectively. In case of acetylene, the scattering of measurement values is large. The results of specimens 10-4 and 19-5 where quantity of transverse shrinkage is especially large are shown by white-painted square and the results of others are shown by black-painted circle. The relation between quantity of transverse shrinkage $D_t$ and heat input parameter $Q/T$ has a good proportional relationship except two test specimens above-mentioned. In case of propane, the scattering of measurement values is also large. The results of specimens 10-5 and 10-6 where quantity of transverse shrinkage is especially small are shown by white-painted square and the results of others are shown by black-painted circle. The relation between quantity of transverse shrinkage $D_t$ and heat input parameter $Q/T$ has a good proportional relationship except two test specimens above-mentioned. Calculating $\alpha_1$ in eqn (3) from figures 6 and 7, the relation between quantity of transverse shrinkage $D_t$ and heat input parameter $Q/T$ is approximately given by the following experimental equations.

$$D_t\,(10^{-3}\text{mm}) = 0.996Q/T\ (\text{kJ/m})/\text{mm} \quad (\text{acetylene}) \qquad (12\text{-}1)$$

$$D_t\,(\text{m}) = 0.205Q/(TE)\ (\text{J/N}) \quad (\text{acetylene}) \qquad (12\text{-}2)$$

$$D_t\,(10^{-3}\text{mm}) = 1.081Q/T\ (\text{kJ/m})/\text{mm} \quad (\text{propane}) \qquad (13\text{-}1)$$

$$D_t\,(\text{m}) = 0.222Q/(TE)\ (\text{J/N}) \quad (\text{propane}) \qquad (13\text{-}2)$$

### 3.2 Results of accuracy confirmation experiment

On several heating conditions, the experimental values of curvature radius obtained by measurement were compared to the predicted values of that calculated from experimental eqns (8), (9) obtained from fundamental experiment. Results are shown in figure 8. On propane, the results of 10mm thickness specimens were deleted because of the distorted buckling. The thinner plate thickness is, the larger the real curvature radius is compared with the calculated one (insufficient bending). The thicker plate thickness is, the smaller the real curvature radius is compared with the calculated one (excess bending). Though heating conditions processing cylinder whose curvature radius is about $R$ = 2000mm were selected on each test specimens, the thicker plate thickness is, the wider the breadth of heat affected zone by each Line-Heating is because of the heating condition where the gas flow rate is large and the heating velocity is slow. In case of bending processing cylinder using many heating lines different from fundamental experiment, they are influenced on each other because of the wide heat affected zone. Therefore, it seems that the curvature radius became small (excess bending) because the current heated area was restricted by plasticity deformation on surrounding heat affected zone.

### 3.3 Unified expression of shrinkage both longitudinal and transverse

On inherent stress method [1], [2], angular distortion, longitudinal shrinkage and transverse shrinkage are expressed by single shrinkage force proportional to quantity of heat input. It is able to explain that eqns (10), (11), (12-2), (13-2) are expressed separately into two directions on the basis of the following equation.

$$F_t\,(\text{N}) = D_t\,TE\,(\text{N}) = \alpha Q\ (\text{kJ/m}) \qquad (14)$$

According to this equation, $\alpha_1 = \alpha_2 = (\alpha_1+\alpha_2)/2$ = 0.220 (acetylene) or 0.215 (propane). Therefore, longitudinal shrinkage and transverse shrinkage are unified to the following equations.

$$F_t\,(\text{N}) = D_t\,TE\,(\text{N}) = 0.220Q\ (\text{kJ/m}) \quad (\text{acetylene}) \qquad (15)$$

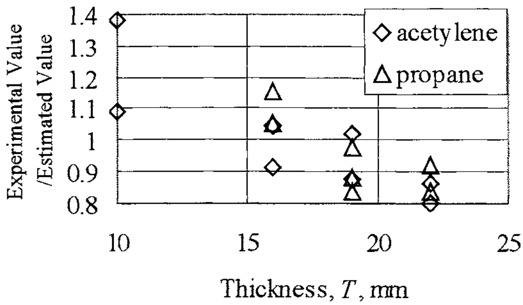


Figure 8: The curvature ratio on bending processing cylinder

$$F_t\,(\text{N}) = D_t\,TE\,(\text{N}) = 0.215Q\,(\text{kJ/m}) \quad (\text{propane}) \qquad (16)$$

Tendon Force $F_t$ is given by White's experimental equation obtained in welding research.

$$F_t\,(\text{N}) = 0.200Q\,(\text{kJ/m}) \qquad (17)$$

In reference [3], it is also concluded that eqn (17) is available on Line-Heating processing. On this research, the values of this $\alpha$ in eqns (15) and (16) are about 10% larger than the coefficient in White's equation. This reason seems to be the experimental error caused by the accuracy of heating processing (it is difficult to make fine adjustment of distance between gas touch corn and plate surface), the accuracy of measurement (the error about 0.05mm is generated by visual measurement) and the accuracy of analysis (it is not clear how to treat and decide the lacking of measurement data and unusual measurement value caused by the electrical noise). For unifying angular distortion, quantification of additional three constants except $\alpha$ mentioned-above is required.

## Acknowledgement

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