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Local Heating for Reducing Residual Stress and Fatigue-performance Improvement of Welded Joints

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ABSTRACT: This study conducts a series of experiments and numerical simulations to explore the effectiveness of local induction heating in reducing welding residual stress and enhancing the fatigue life of steel structural members. The primary focus was on diminishing tensile residual stress around box-welded joints using an induction heating device. The investigation encompassed various heating conditions, including temperature, position, and sequence, to examine the reduction of welding residual stress. Experimental and analytical approaches were utilized to assess these conditions. Residual stress measurements confirmed the efficacy of stress reduction through local heating, while numerical simulations elucidated the underlying stress reduction mechanism. Additionally, the study evaluated the impact of this residual stress reduction on the fatigue performance of the box-welded joints. It was found that fatigue life could be significantly improved by local heating under two distinct loading conditions in which tensile and compressive stresses were applied to the weld toe.

Keywords: Welding, residual stress, box-welded joints, fatigue, finite element analysis

23 **1. Introduction**

24 The fatigue life of steel structures is crucial for ensuring long-term durability. Fatigue damage, such as cracks, often
25 originates from welded parts due to stress concentration influenced by their geometric shapes and the tensile residual stress
26 from welding. Various techniques have been explored to enhance the fatigue performance of welded joints. Tungsten inert
27 gas (TIG) dressing and grinding have been utilized to improve the geometric shapes of weld toes and reduce stress
28 concentrations [1-3]. Methods such as hammer peening, shot peening, needle peening, and high-frequency mechanical
29 impact (HFMI) techniques, including ultrasonic impact treatment, are employed to enhance the metal structure around
30 welded parts and induce compressive residual stress [4-7]. While these methods are effective and popular for improving
31 fatigue performance, they require direct access to the welded areas, necessitating the attachment of mechanical tools to the
32 weld bead or base metal surface. In structures like steel bridges, where welded parts are often in narrow and complex spaces,
33 applying these mechanical methods can be challenging or impossible. Although it is feasible to treat the weld toe
34 mechanically in narrow and complex welded parts, mechanically treating fatigue cracks originating from the weld root is
35 not possible [8].

36 As an alternative, the authors have investigated post-weld heat treatment (PWHT) for fatigue performance improvement.
37 We explored the use of portable and small heat sources, such as sheet-type ceramic heaters and induction heaters, for
38 applying PWHT to complex structural parts [9-14]. It has been demonstrated that PWHT can reduce welding residual stress
39 and enhance the fatigue life of welded joints. However, traditional PWHT requires prolonged exposure to high temperatures
40 (around 600 °C) to reduce welding residual stress effectively. To address this issue, we have explored an alternative heating
41 method, specifically localized heating, to modify the welding residual stress state. Rapid heating is essential in this method

42 to generate a temperature differential between heated and unheated areas. Moreover, precise temperature control is
43 necessary to ensure worker safety and prevent overheating. An induction heating (IH) device was chosen for its ability to
44 rapidly and locally increase the temperature of magnetic materials like steel through electric resistance against eddy currents
45 generated by an induction coil. IH allows for remote heating without direct contact with the target area, and heat conduction
46 may be beneficial for heating positions away from the induction coil. The rapid and localized temperature increase achieved
47 by IH, along with its high controllability (attributable to the use of an electric power supply) and enhanced safety (owing
48 to the absence of flames), makes it an ideal choice.

49 This study focuses on identifying optimal IH conditions for reducing residual stress in box-welded parts of gusset joints,
50 where numerous fatigue damages have been reported in steel bridge structures [15]. We have confirmed the potential of
51 stress reduction using localized IH around the box-welded parts [16, 17]. In addition, we investigated reasonable and
52 effective heating conditions, such as heating position and sequence, through an analytical approach. The study also includes
53 an evaluation of fatigue loading test results to assess the impact of stress reduction through proposed local heating on the
54 fatigue performance of box-welded joints.

55

56 **2. Concept of residual stress reduction by local heating**

57 **2.1 Basic concept of local heating**

58 In this study, we focus on reducing the residual stress component that crosses the weld line of the box-welded part, as
59 fatigue cracks often occur at the toe of the box-welded part [15]. **Fig. 1** illustrates the concept of reducing residual stress
60 through local heating [16].

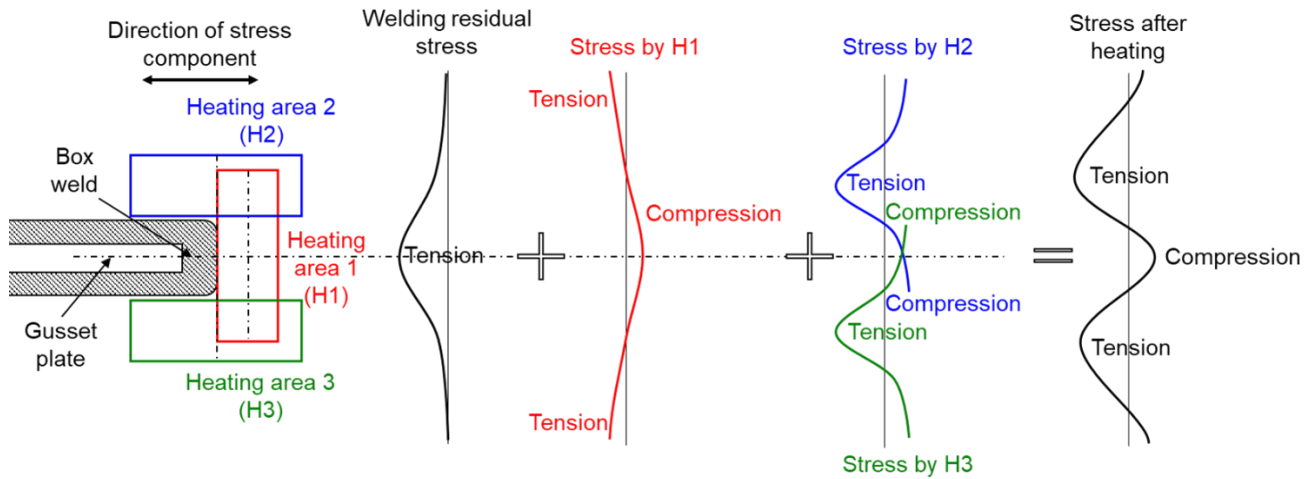


Fig. 1 Concept of local heating.

Initially, the front of the box-welded part is heated, a process we refer to as ‘heating 1 (H1).’ During the heating phase, the expansion of the heated part is constrained by the surrounding material at normal temperature, generating compressive stress at the heated location. Subsequently, as the heated part cools and contracts, this shrinkage is also restricted by the surrounding area. This cooling phase induces tensile stress in the same area. The resulting stress state depends on the relative magnitudes of these compressive and tensile stresses. When the compressive stress exceeds the tensile stress, it remains the predominant stress. The objective is for this remaining compressive stress to overlap with the original tensile welding residual stress at the weld toe.

Next, the left and right sides of the box-welded parts are heated, termed ‘heating 2 (H2)’ and ‘heating 3 (H3),’ respectively. The mechanism here is similar to that of H1: compressive stress is induced in the heated area during the rise in temperature, and tensile stress develops during cooling. This tensile stress, in turn, creates additional compressive stress further from the heated area to balance the forces within the section. This process is analogous to the mechanism of general welding residual stress in the direction of the weld. By precisely controlling the heating positions, it is possible to superimpose compressive stress over the original tensile welding residual stress at the weld toe. The combination of these heating

76 processes can effectively reduce the original tensile welding residual stress at the weld toe. The efficacy of this stress state
77 control mechanism has been validated through experimental and analytical approaches in previous studies [16].

78 **2.2 IH device**

79 To implement the proposed mechanism for stress state control in this study, a heat source capable of generating residual
80 stress similar to welding is required. This heat source must facilitate rapid heating to create a temperature differential
81 between the heated and non-heated areas. Consequently, IH was chosen for this purpose. IH efficiently raises the
82 temperature of magnetic materials, such as steel, through electric resistance against eddy currents generated by the
83 induction coil. Additionally, IH offers high controllability and safety, as it operates without flames and relies on electric
84 power. These characteristics make IH suitable for both shop fabrication and on-site maintenance of steel bridge structures.
85 **Fig. 2** illustrates the IH device used in this study. The electric power generator measures 450 mm in width, 740 mm in
86 depth, and 855 mm in height, with a weight of 90 kg. Its maximum power and frequency capabilities are 20 kW and $28 \pm$
87 8 kHz, respectively. The water-cooling unit is approximately the same size as the power supply, and the coil measures 40
88 mm $\times$ 110 mm. The weight of the coil is 0.65 kg. The weight of the part including the coil and the cables for electric power
89 and chiller water is around 5 kg. It might be possible for workers to bring the coil to the bridge members and attach it to
90 the target parts. The dimensions and weight of these devices are manageable for both in-shop fabrication and on-site
91 maintenance tasks involving steel bridge members.

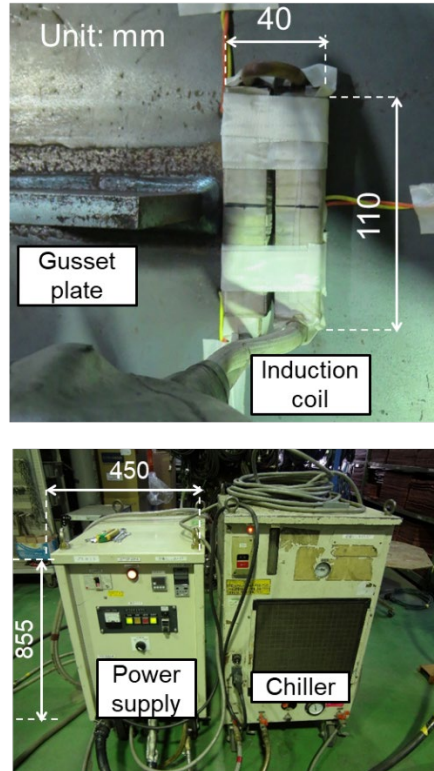


Fig. 2 IH device.

2.3 Heating temperature

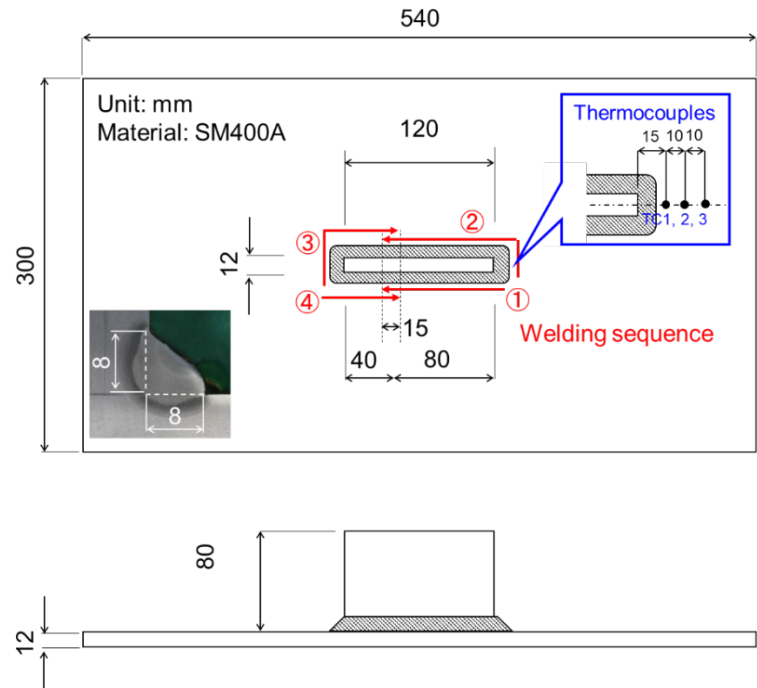
The heating temperature is a critical factor in controlling stress states through local heating. When applying heat to steel structural components, it is essential to avoid altering the material characteristics and mechanical properties. Therefore, the heating temperature must remain below the steel's transformation or recrystallization temperature [18]. In this study, the recrystallization temperature of steel, 450 °C, was established as the upper limit for local heating. Additionally, a target temperature of 350 °C was set to provide a safe margin, thereby preventing overheating.

3. Local heating experiment

3.1 Experimental specimen

Fig. 3 presents the dimensions and shape of the specimen used in this study. The base plate measures 540 mm × 300 mm,

104 and the gusset plate is 120 mm × 80 mm, both with a thickness of 12 mm. The material used is SM400A, as specified by
 105 JIS G3106. **Table 1** details the chemical compositions and mechanical properties of this material.



106
 107 **Fig. 3** Box-welded joint specimen.

108
 109 **Table 1** Material information of base metal (BM) and weld metal (WM).

	Chemical compositions (mass%)					Mechanical properties		
	C	Si	Mn	P	S	Yield strength (N/mm ²)	Tensile strength (N/mm ²)	Elongation (%)
BM	0.17	0.14	0.64	0.010	0.004	293	441	30
WM	0.05	0.60	1.30	0.013	0.012	480	570	25

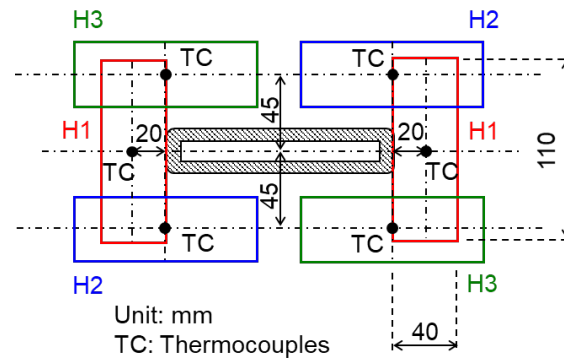
110
 111 The gusset plate was attached to the base plate using gas metal arc welding. The welding wire, conforming to JIS Z 3313
 112 standards and of the same grade as the base metal, was used. **Table 1** also includes the chemical compositions and
 113 mechanical properties of the welding wire (catalog values). The welding conditions involved a voltage of 30 V, a current

114 of 260 A, and a speed of 5.5 mm/s. As depicted in **Fig. 3**, four welding passes were executed, with passes 3 and 4
115 overlapping passes 1 and 2 to create a continuous weld line. The overlap length was 15 mm, and the leg length of the weld
116 bead was 8 mm. The temperature history around the box-welded part during welding was monitored using K-type
117 thermocouples attached to the base plate, as shown in **Fig. 3**. The welding residual stress was measured by the X-ray
118 diffraction (XRD) method.

119 **3.2 Heating experiment**

120 The local heating experiment using the IH device was performed on the gusset welded specimens. **Fig. 4** shows the local
121 heating positions. In H1, the edge of the induction coil was positioned at the box-weld toe. For H2 and H3, the center of
122 the induction coil was placed 45 mm from the center of the box-weld toe. This positioning was determined based on
123 previous experimental and analytical studies using the same IH device on steel plate specimens with the same thickness as
124 the gusset welded specimens [10]. These studies suggested that these heating positions could generate compressive residual
125 stress at the center of the box-weld toe by the specified heating conditions. The heating temperature of 350 °C could induce
126 the compressive residual stress to the plate. The heating and cooling rate should be quick and the soaking time should be
127 short based on the purpose of generating the temperature difference between the heated part and the other part. It was
128 shown that the capacity of the IH device used in this study and the natural cooling could achieve this purpose. Furthermore,
129 the residual stress generation is largely affected by the constraint conditions of the specimen. The specimen size (width)
130 corresponds to the degree of the self-constraint. When the specimen is externally fixed by clamping, the residual stress by
131 heating becomes high. The previous study showed that the width of the specimen (300 mm) and no external constraint
132 condition generated a considerable change in residual stress.

133 The heating temperature for each phase was monitored using the same K-type thermocouples as the welding temperature
 134 measurement attached to the centers of the heating areas. As shown in Fig. 4, the positions of the thermocouples are
 135 illustrated by the marks of 'TC.' Once the temperature reached the target of 350 °C, the electric power generator was turned
 136 off.



137
 138 **Fig. 4** Positions and sequence of local heating.

139 During the local heating process, residual stress was measured using the XRD method at the same locations as the state
 140 after welding. The residual stress was measured after H1. Then, H2 and H3 were performed. Finally, the residual stress was
 141 measured again. This alternate heating and measurement made it possible to confirm the change in residual stress during
 142 the local heating.

143

144 4. Finite element (FE) simulation of welding and local heating processes

145 4.1 FE model

146 To simulate the behavior of residual stress reduction through local heating, a thermal elastic–plastic analysis was conducted
 147 [16]. **Fig. 5** depicts the FE model used for this simulation. The analysis was performed using the commercial FE program
 148 ABAQUS Ver. 6.14, which facilitates coupled temperature and displacement analysis. The model utilized 8-node brick

149 elements. The mesh size around the welded parts was decided by referring to previous studies about welding simulation [9,
 150 13]. Initially, the welding process was simulated to generate welding residual stress. This was followed by simulating the
 151 local heating process to examine the behavior of residual stress reduction. Material properties, as shown in **Fig. 6**, were
 152 incorporated into the analysis [19, 20]. The thermal boundary condition included heat transfer from the outer surface but
 153 did not include heat convection and radiation. The mechanical boundary condition was the restraint of rigid-body
 154 displacement.

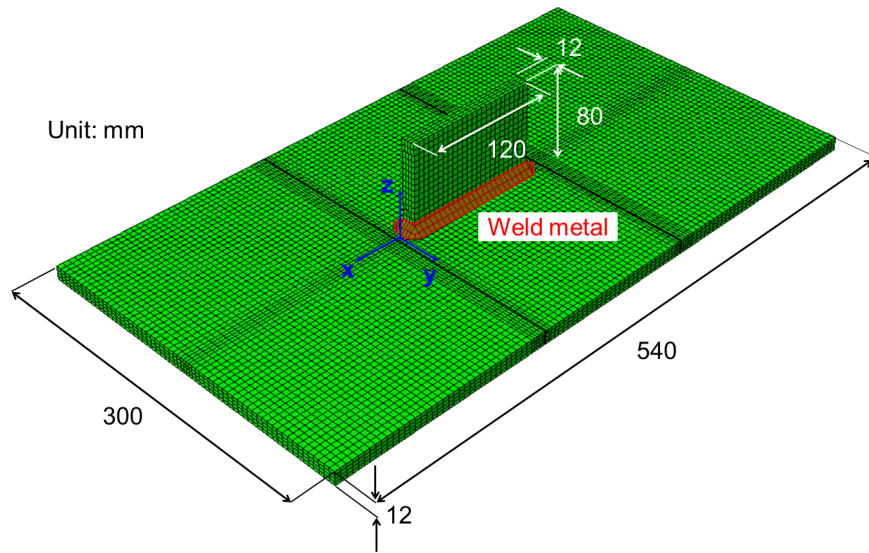
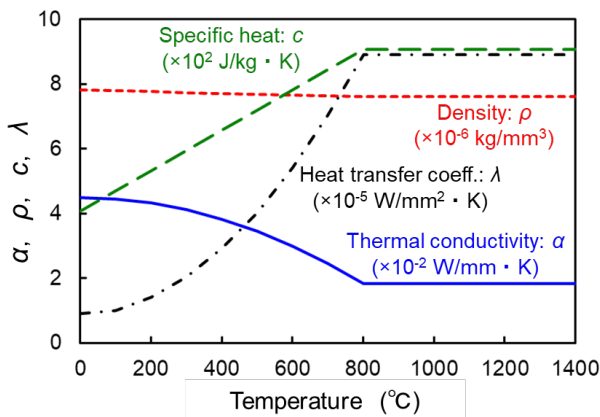
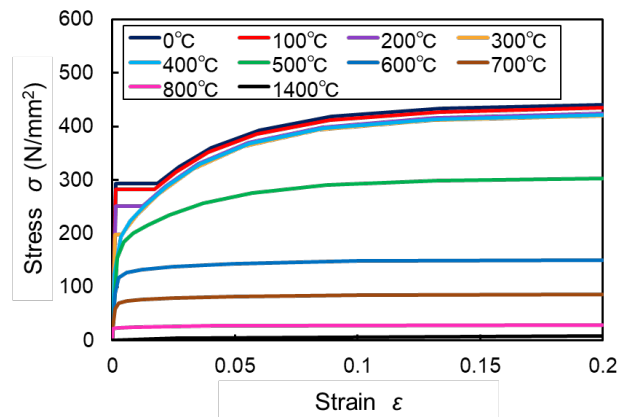


Fig. 5 FE analysis model.



(a) Physical constants.



(b) Stress-strain curves

Fig. 6 Material properties for analysis.

4.2 Simulation of welding process

The simulation of the welding process aimed to generate welding residual stress. The heat input, calculated using Eq. (1) based on the welding conditions, was applied to the weld metal elements:

$$Q_w = \eta_w \frac{EI}{v}, \quad (1)$$

where Q_w is the heat input from welding (J/mm), η_w represents the thermal efficiency of welding (ranging from 0.47 to 0.85) [21], E is the voltage (V), I is the current (A), and v is the speed (mm/s).

The thermal efficiency was adjusted several times to replicate the temperature history observed in the experiment. The heat energy per unit volume decided by this procedure was input to the weld metal elements as uniform body heat flux. The generation and movement of heat input elements were considered. **Fig. 7** compares the welding temperature histories from the experiment and analysis. The experimental results could be simulated with a thermal efficiency of 0.70.

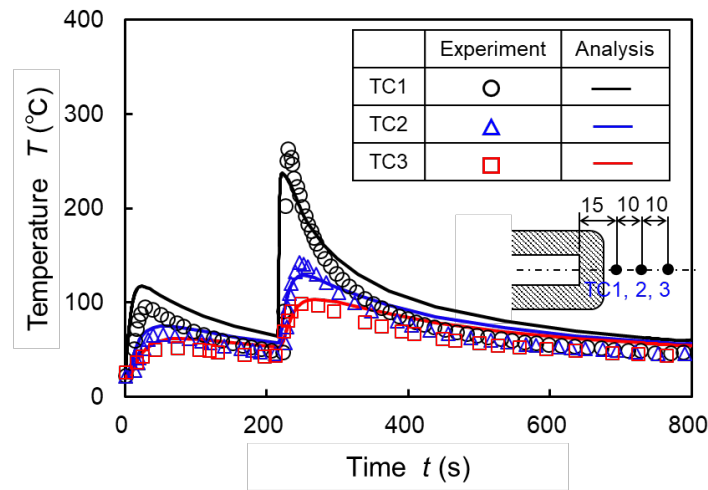


Fig. 7 Welding temperature history.

4.3 Simulation of local heating process

The local heating process was simulated to investigate the reduction of welding residual stress. Heat energy was applied to the areas of H1, H2, and H3. Body heat flux, calculated using Eq. (2), was supplied to the elements corresponding to the

175 heating areas [10]:

$$176 \quad Q_H = \eta_H \frac{P}{V}, \quad (2)$$

177 where Q_H is the heat input from IH (J/mm³), η_H is the thermal efficiency for IH (0.38) [10], P represents the electric
178 power (J), and V is the volume of the heating part (mm³).

179 **Fig. 8** shows the temperature histories during local heating as obtained from the experiment and analysis. The symbols
180 corresponding to H1, H2, and H3 represent the temperature histories recorded by thermocouples at the center of each
181 heating area. The analysis was able to replicate the experimental results. **Fig. 9** illustrates the residual stress distribution
182 around the box-welded part before and after the local heating process, focusing on the stress component in the longitudinal
183 direction of the joint along the x-axis. The symbols represent the experimental results measured by the XRD method, while
184 the lines represent the analysis results. This comparison confirms that the experimental results were successfully reproduced
185 by the analysis, validating the analysis model for both welding and local heating processes. **Fig. 10** presents the residual
186 stress distribution in the longitudinal direction of the joint along the y-axis, as determined by the analysis. The stress
187 distribution pattern closely matches the assumed stress state depicted in **Fig. 1**. By the way, the stress in the areas of H2
188 and H3 inevitably becomes tension. If a fatigue crack generated from the weld toe reaches this tensile residual stress area,
189 the crack propagation will be accelerated. This feature of the stress distribution after the local heating should be noted from
190 the viewpoint of the crack initiation and propagation behavior.

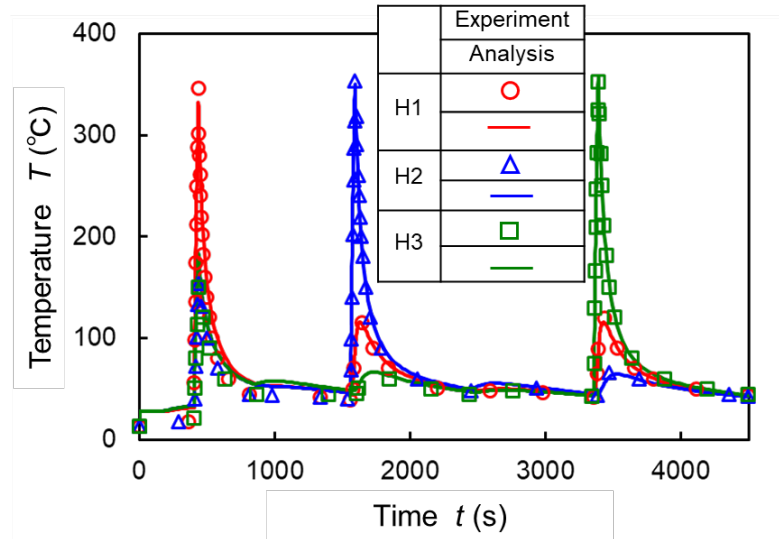


Fig. 8 Temperature histories of local heating.

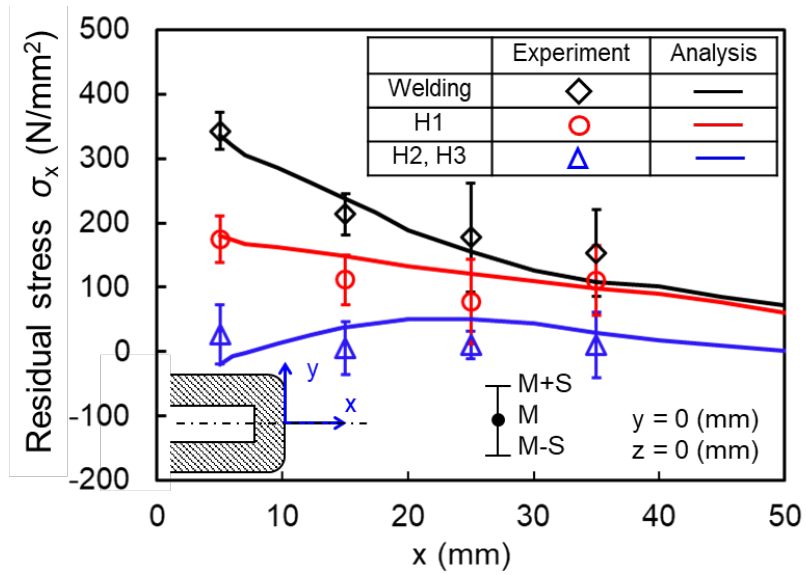


Fig. 9 Residual stress by welding and local heating.

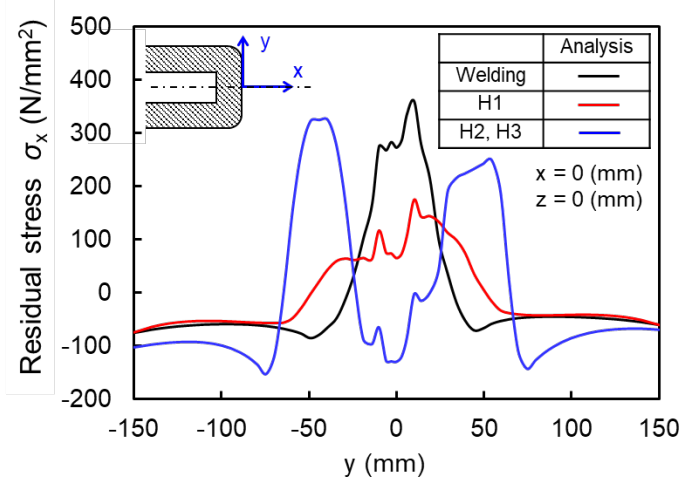


Fig. 10 Residual stress distribution along the y-axis.

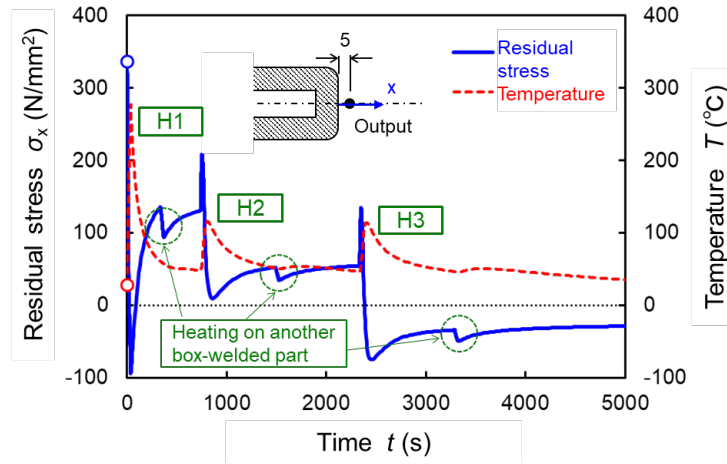
4.4 Mechanism of welding residual stress reduction by local heating

Fig. 11 illustrates the change in stress at a point 5 mm from the weld toe during the local heating process. Initially, the welding residual stress was 340 N/mm². During H1, the thermal expansion of the heated part was constrained by the surrounding areas, inducing significant compressive stress resulting in a stress value of -94 N/mm² at the measured point. However, as the H1 area cooled and contracted, the shrinkage was also restrained, leading to a recovery of stress towards the tensile side, eventually reaching 136 N/mm². The milder temperature change during the cooling phase contributed to this stress level. Additionally, the influence of H1 on another box-welded part was observed, confirming a stress reduction of 40 N/mm². Ultimately, the stress stabilized at 130 N/mm² after a gradual temperature decrease.

At the 750 s mark in H2, the stress at the measured point increased to 210 N/mm² during a 40 s heating period. Following heating, the stress was reduced to 15 N/mm² for 100 s and then gradually increased to 50 N/mm², influenced by the mild temperature rise and H2 on another part. The stress pattern in H3, occurring at 2350 s, was similar to that of H2, with the final stress at the noted point reaching -30 N/mm². The heating areas of H2 and H3, located 45 mm from the weld toe in the cross direction, developed tensile stress following heating, while compressive stress formed around these areas to

210 balance section forces. This compressive stress at the weld toe contributed to the observed reduction in stress.

211 These results validate the hypothesis of residual stress reduction through local heating proposed in this study.



212
213 **Fig. 11** Stress history by local heating.

214 4.5 Effect of stress reduction on weld root

215 This study's experiment observed a notable residual stress reduction at the weld toe, a critical area due to the frequent
216 occurrence of fatigue cracks. However, fatigue crack initiation and propagation at the weld root also pose significant
217 concerns in steel structural members [8]. Existing countermeasures such as TIG dressing, peening, and HFMI are primarily
218 applicable to weld toes and cannot be used on inaccessible weld roots. Addressing these challenges, this study explored the
219 possibility of reducing welding residual stress at the weld root through analytical results.

220 **Fig. 12** shows the residual stress along the x-axis through both the weld toe and weld root. **Fig. 13** shows the residual stress
221 distribution around the weld root before and after local heating. The weld root geometry was modeled from the macroscopic
222 photograph of the cross-section of the weld bead (**Fig. 3**). Although the penetration of the weld metal to the base metal was
223 not considered, the tendency of the welding residual stress around the weld root could be simulated. Therefore, it might be
224 possible to discuss the change in residual stress by the local heating based on this model. The local heating reduced the

stresses at the weld toe and the weld root, with welding residual stresses at the weld root decreasing from 284 N/mm² to 40 N/mm² due to the three stages of local heating. Additionally, **Fig. 13** shows that the local heating could reduce the welding residual stress inside the thickness. The residual stress reduction could reach the backside of the base plate. These findings suggest that the local heating approach proposed in this study could effectively reduce residual stress at both the weld toe and weld root.

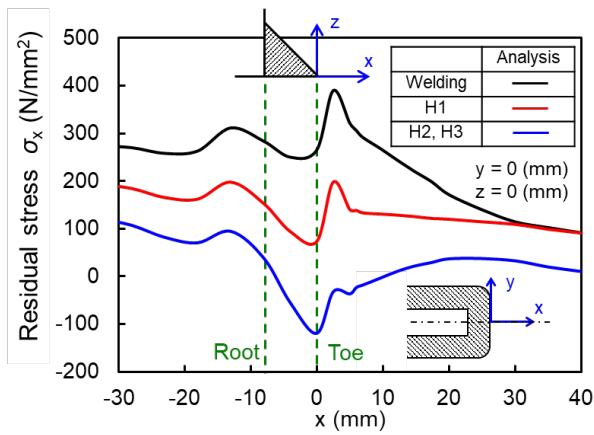


Fig. 12 Residual stress distribution along the x-axis.

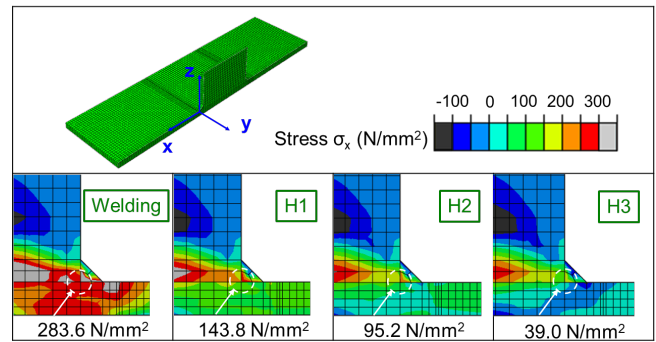


Fig. 13 Change in residual stress around weld root.

5. Influence of local heating condition on residual stress reduction

5.1 Heating sequence

To investigate the impact of local heating conditions on the degree of residual stress reduction, a series of analyses were conducted, focusing first on the heating sequence. In this variation, H2 and H3 preceded H1, maintaining the same heating temperature and cooling conditions. The target heating temperature and duration were set at 350 °C and 40 s. H3 commenced after the center of the H2 area cooled to 50 °C, followed by H1 after the H3 area reached 50 °C. **Fig. 14(a)** illustrates the stress changes 5 mm from the weld toe during this heating sequence. Similar to the original experiment, compressive stresses were induced at the measured point by H2 and H3, reducing the welding residual stress from 340

241 N/mm² to 20 N/mm². Subsequently, H1 was applied, initially inducing compressive stress but later recovering to the tensile
242 side as it cooled, resulting in a final stress of 60 N/mm² at the measured point.

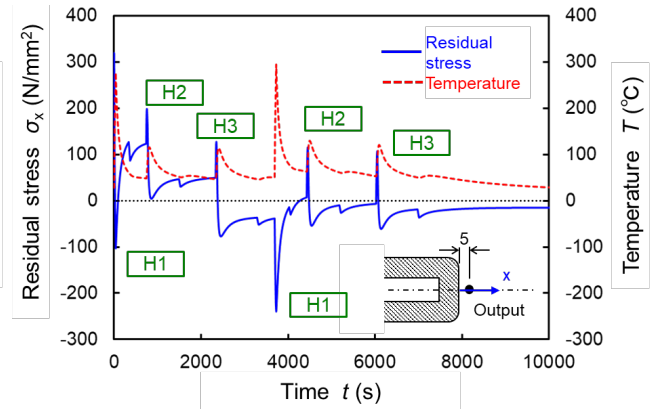
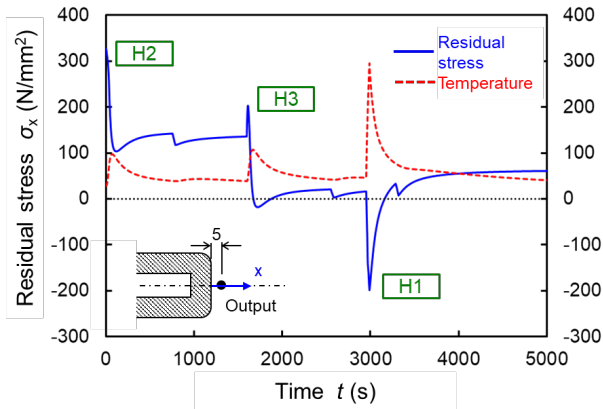
243 5.2 Heating frequency

244 The influence of heating frequency was also examined. The basic heating sequence of H1, H2, and H3 was repeated twice.

245 **Fig. 14(b)** shows the stress changes at the same point during this process. The first heating cycle reduced the stress to -50
246 N/mm². Thus, the second cycle started from a lower stress level. The stress reduction effect of H1 in the second cycle was
247 less pronounced, and the final stress level after two heating cycles was similar to that of the basic condition with one cycle.
248 Ultimately, the stress settled at -50 N/mm².

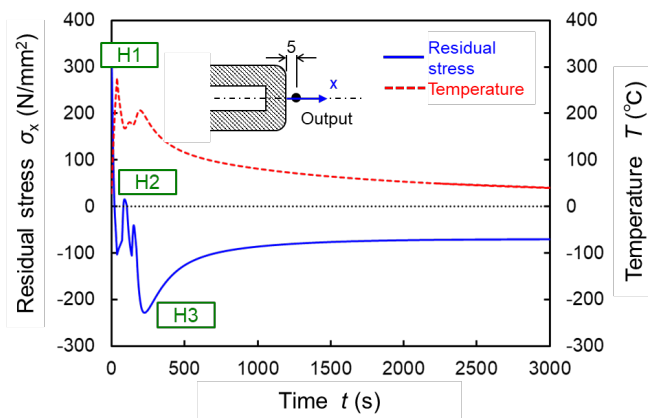
249 5.3 Waiting time

250 Lastly, the waiting time between H1, H2, and H3 was examined. In the standard experimental condition, the next heating
251 phase started after the previous one ended and the temperature reached 50 °C. In this analysis, the waiting time was
252 eliminated, and subsequent heating began immediately after the previous phase. **Fig. 14(c)** shows the stress changes under
253 this condition. The stress was reduced during the H1 process, and before it could recover, H2 and H3 were applied. This
254 approach led to a greater stress reduction effect compared to the basic condition, with the largest compressive stress of -70
255 N/mm² remaining at the measured point. Eliminating the waiting time between heating phases appears beneficial for
256 achieving greater stress reduction and reducing overall working time.



(a) Influence of heating sequence.

(b) Influence of heating frequency



(c) Influence of waiting time

Fig. 14 Influence of heating conditions on residual stress.

6. Fatigue experiment

6.1 Experimental procedure

The fatigue experiments were conducted on specimens both with and without local heating to examine the impact of residual stress reduction by local heating on fatigue performance. The experimental setup, depicted in **Fig. 15**, employed a four-point bending approach. The box-welded gusset joints were situated between the two loading points, ensuring a

269 uniform bending moment in this region. Two loading patterns were used in these experiments: one where tensile stress
 270 from the bending load was applied to the gusset plate-attached surface of the specimens, resulting in tensile stress at the
 271 box-welded part (referred to as the tension loading pattern, as shown in **Fig. 15(a)**) [16], and another where the specimen
 272 was inverted, applying compressive stress to the box-welded part (referred to as the compression loading pattern, as shown
 273 in **Fig. 15(b)**) [17].

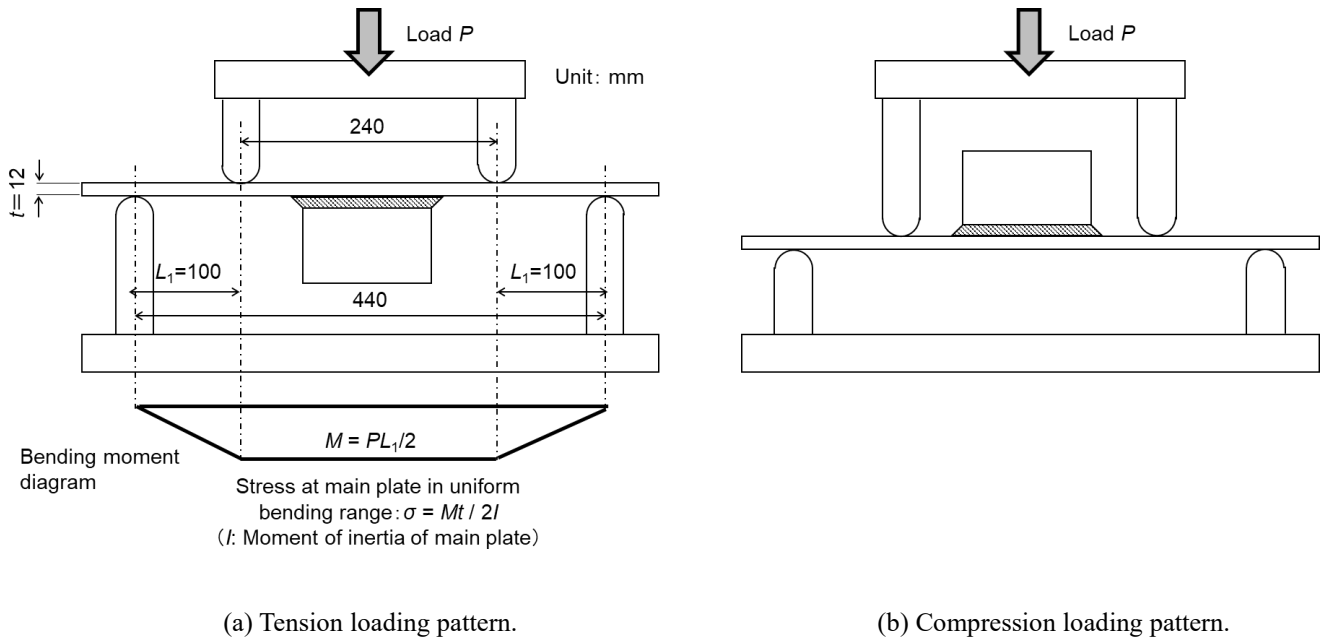


Fig. 15 Setup of fatigue experiments.

277 The applied nominal stress was calculated using Eq. (3), representing the stress at the specimen's surface due to the uniform
 278 bending moment. The stress range applied was the difference between the maximum and minimum stresses, with the
 279 minimum stress magnitude being 10% of the maximum.

$$280 \quad \sigma_a = \frac{M}{W} = \frac{PL_1/2 \cdot t}{bt^3/12 \cdot 2}, \quad (3)$$

281 where σ_a is the applied nominal stress (N/mm²), M is the bending moment (N·mm), W is the section modulus of the
 282 base plate (mm³), P is the load (N), L_1 is the distance from the support point to the loading point (mm), b is the breadth

283 of the base plate (mm), and t is the thickness of the base plate (mm).

284 Strain gauges were attached around the welded part to detect crack initiation. A decrease in strain amplitude indicated crack

285 initiation, as load transfer was impeded by the crack. The definition of fatigue life in this experiment was the number of

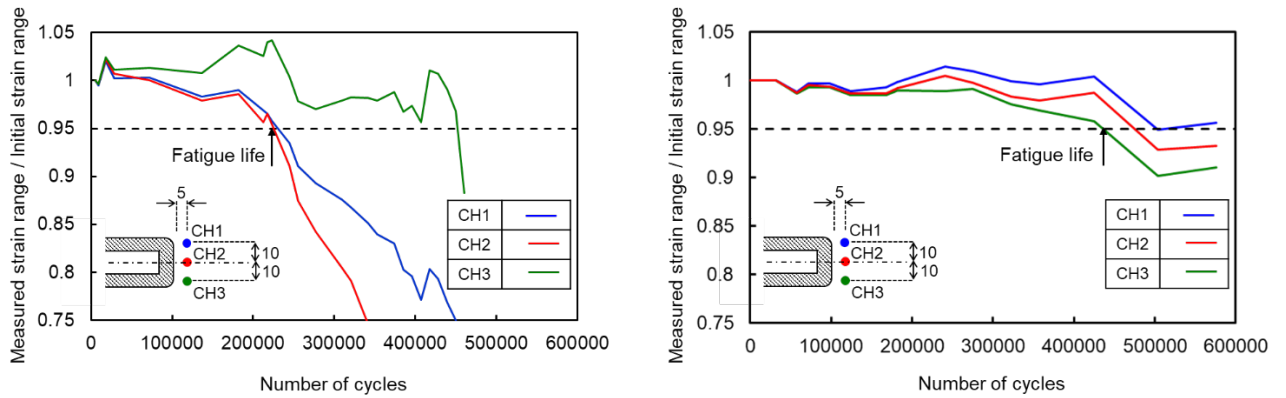
286 loading cycles at which the strain amplitude dropped by 5% from its initial value [13]. **Fig. 16** illustrates examples of

287 changes in strain amplitude, showing gradual decreases in both tension and compression loading patterns. Upon reaching

288 the defined fatigue life, fatigue cracks were inspected using magnetic particle testing. **Fig. 17** presents an example of a

289 detected fatigue crack. Cracks were observed at the box-welded toe in specimens where the strain amplitude dropped by

290 more than 5% from the initial value.



(a) Tension loading pattern.

(b) Compression loading pattern.

Fig. 16 Change in strain amplitude.

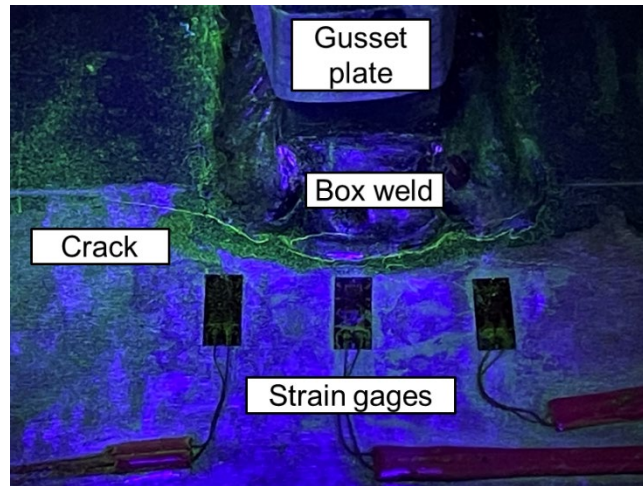
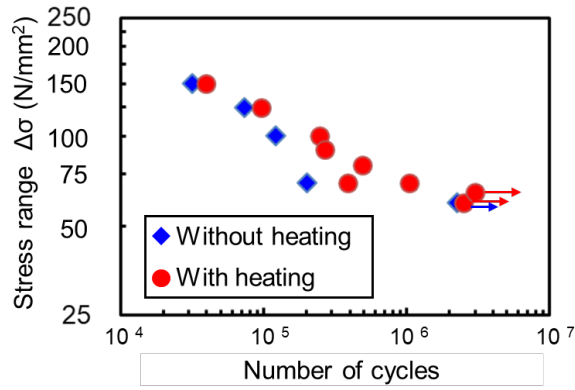


Fig. 17 Example of a fatigue crack.

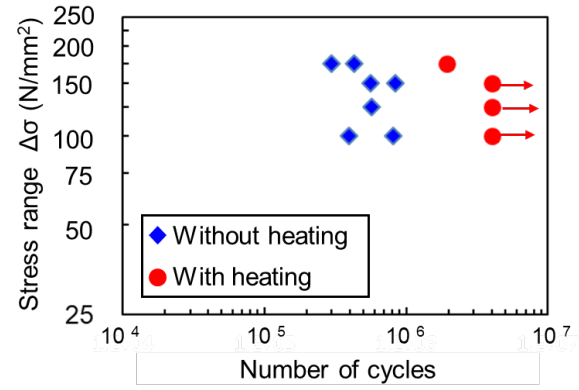
6.2 Results and discussions

Fig. 18 presents the results of the fatigue experiments. Before discussing the improvement of the fatigue life by the local heating, it was natural that the fatigue life of the specimens with and without local heating in the tension loading pattern was entirely shorter than that in the compression loading pattern. The definition of the fatigue life in this study was the number of loading cycles at which the strain amplitude dropped by 5% from its initial value. Although the crack growth rate was not measured directly, the gradual decrease of the strain amplitude corresponded to the propagation of the fatigue crack. The difference in the fatigue life between the tension and compression loading patterns showed that the crack growth rate in the tension loading pattern might be faster than that in the compression loading pattern.

In both loading patterns, specimens that underwent local heating demonstrated longer fatigue lives compared to the weld specimens. This indicates the significant effect of residual stress reduction by local heating on enhancing fatigue life. However, the extent of improvement in fatigue life was more pronounced in the compression loading pattern than in the tension loading pattern.



(a) Tension loading pattern.



(b) Compression loading pattern.

Fig. 18 Results of fatigue experiment.

The reduction in residual stress contributed to a decrease in the mean stress level of the cyclic loading. Specimens without local heating exhibited high mean stress levels, equivalent to the welding residual stress of over 300 N/mm². Specimens that underwent local heating likely had nearly zero mean stress levels. In the tension loading pattern, an improvement in fatigue life due to local heating was observed within the 70 N/mm² to 100 N/mm² stress range. The fatigue life of the specimen without local heating under 70 N/mm² of the stress range was 199,800 cycles. Those of the specimens with local heating were 387,720 cycles and 1,038,200 cycles. The fatigue life of the specimen without local heating under 100 N/mm² of the stress range was 122,400 cycles. That of the specimen with local heating was 244,800 cycles. The fatigue life of the locally heated specimens was 2 to 5 times longer than that of the specimens without local heating. However, in higher stress ranges exceeding 125 N/mm², the fatigue life of specimens with and without local heating was similar. Even with reduced welding residual stress, the local stress at the weld toe might remain high due to stress concentration. When the applied nominal stress is high, local stress at the weld toe may exceed the material's yield point, regardless of local heating, potentially diminishing the impact of residual stress reduction on fatigue life improvement. Furthermore, it is known that

325 welding residual stress is reduced under cyclic loading due to the plasticity of the material [22]. When the magnitude of
326 the applied external load is large, the degree of the residual stress reduction is also large because the large plastic strain is
327 induced to the welded part. It might be that the welding residual stress of the specimen without local heating was reduced
328 by the cyclic loading of the high-stress ranges over 125 N/mm². As a result, the stress states of the specimens with and
329 without local heating became so similar that there were few differences in fatigue life of them.

330 In the compression loading pattern, the stress state of the locally heated specimens was likely entirely compressive under
331 cyclic loads, implying both maximum and minimum stresses were compressive. For specimens without local heating, the
332 maximum stress might have been tensile due to the original high tensile residual stress. Thus, the mean stress level of the
333 specimens with local heating could be considerably lower than that of the specimens without local heating, leading to a
334 more significant improvement in fatigue life in the compression loading pattern.

335 The locally heated specimen under the stress range of 175 N/mm² reached the fatigue life defined as the number of loading
336 cycles at which the strain amplitude dropped by 5% from its initial value, even though the stress state might be pure
337 compression due to the residual stress reduction. Although the magnetic particle testing was performed around the weld
338 toe after finishing the loading, clear fatigue cracks were not inspected at the weld toe but a small crack was observed on
339 the irregular part of the weld bead. Therefore, this data might not be the fracture of the specimen and should be treated as
340 a reference.

341 An improvement in fatigue life due to local heating was observed in stress ranges exceeding 100 N/mm², with the locally
342 heated specimens exhibiting a fatigue life 5 to 10 times longer than those without local heating. This pattern aligns with
343 previous studies that observed fatigue life improvement due to PWHT on cover plate specimens [13]. The effect of fatigue

344 life improvement from residual stress reduction via local heating is significantly influenced by the applied stress pattern
345 (tension or compression). Thus, the application of local heating should be considered based on the stress pattern and the
346 magnitude of stress levels in the targeted welded joints.

347

348 7. Conclusions

349 A series of experiments and analyses on box-welded specimens were conducted to investigate the effects of residual stress
350 reduction through local induction heating. Additionally, the improvement in fatigue life resulting from residual stress
351 reduction was verified through fatigue experiments using different loading patterns. The key findings are summarized as
352 follows:

353 (1) Local heating and residual stress reduction: The basic concept of local heating for reducing residual stress in box-
354 welded parts was detailed. An induction heating device was chosen as the heat source, fitting the stress reduction
355 concept. Local heating experiments on box-welded joint specimens demonstrated that a three-step heating process at
356 350 °C effectively reduced tensile residual stress at the weld toe from 340 N/mm² to 30 N/mm². The experimental
357 results were successfully simulated using thermal elastic–plastic analysis, validating the analysis model and elucidating
358 the stress reduction mechanism.

359 (2) Impact on weld toe and root: Numerical simulations confirmed that local heating reduced stress at both the weld toe
360 and root. Welding residual stress at the weld root decreased from 284 N/mm² to 40 N/mm² due to the three-step heating
361 process. These results suggest that the local heating approach proposed in this study could be effective in reducing
362 residual stress at both these critical points.

363 (3) Optimization of heating conditions: Further numerical simulations explored more effective local heating conditions
364 for greater welding residual stress reduction than that achieved in the experiments. These simulations revealed that
365 heating in front of the weld toe is most effective when the original stress level is high. Moreover, eliminating the
366 waiting time between heating steps could not only lead to larger stress reductions but also save total working time.

367 (4) Fatigue life improvement in different loading patterns: Fatigue experiments on both as-welded and locally heated
368 specimens were performed under conditions applying either tensile or compressive stresses at the weld toe (tension or
369 compression loading patterns, respectively). While fatigue life improvement was observed in both loading patterns,
370 the enhancement was more significant in the compression loading pattern. Therefore, the application of local heating
371 should be based on the specific stress pattern and magnitude of the target welded joints.

372

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377 **Author contributions**

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379 Validation: M. Hirohata; Investigation: M. Hirohata, K.-H. Chang, T. Suzuki, and H. Konishi; Writing: M. Hirohata;

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381 All authors have read and agreed to the published version of the manuscript.

382 **Conflicts of interest**

383 The authors declare no conflict of interest.

384

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