JFE TECHNICAL REPORT
No. 20 (Mar. 2015)

Method of Improving Fatigue Strength by Peening on Base Metal and Development of Mechanized System†

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Abstract:

Hammer peening is used for improving fatigue strength of welded joint. In general peening method impacts are introduced on the weld toe, however, in this new method impacts are introduced on the base material near the weld toe. Since impacts are introduced on the flat base metal, this method does not affect the quality of the weld and stable fatigue strength can be achieved. Through finite element (FE)-analysis, the correlation between the area of depression and the fatigue strength was confirmed, and the threshold level required for improving fatigue strength was defined. Also in order to expand applicability, faster treatment method by using mechanized system was developed.

1. Introduction

Aging of social capital that was constructed in Japan during this country's high economic growth period is progressing rapidly and has become a serious problem. In response to the ceiling panel collapse accident of Chuo Expressway Sasago Tunnel in December 2012, Ministry of Land, Infrastructure, Transport and Tourism positioned 2013 as the "First Year of the Social Capital Maintenance Era"[1)] and is implementing countermeasures for deterioration of infrastructure with age.

In steel bridges, the fatigue strength of welded joints is one of the critical elements that determine the life of the structure. Various methods for improving fatigue strength have been proposed. Hammer peening (hereinafter, HP) is a method for preventing initiation of fatigue cracks, in which impact is applied to the weld toe region to introduce compressive residual stress. In recent years, ultrasonic peening techniques, beginning with Ultrasonic Impact Treatment (UIT)[2)], have been applied practically. These techniques use ultrasonic vibration, which can reduce the noise and reaction force that are issues with conventional HP. However, care is necessary, as peening causes the defect called inclusion, which reduces fatigue strength; to avoid this problem, grinder treatment before peening is recommended[3)].

In the hammer peening on base metal method developed in this research, hammering is performed on the base material near the weld toe rather than on the weld toe region, as in the conventional method (**Fig. 1**). Performing hammering on the base material with a general-purpose air tool (**Photo 1**) by applying ICR Treatment (Impact Crack Closure Retrofit Treatment) developed by Yamada et al.[4)] introduces compressive residual stress in the vicinity of the weld toe, which is the point of origin for fatigue cracks, and as a result, the fatigue strength of the welded joint is improved. As an advantage of the developed method, since the problem of inclusion in the conventional method is virtually eliminated, it is not necessary to perform grinder treatment along the entire line of the weld bead prior to peening.

With conventional HP, it was difficult to confirm the fatigue strength improvement effect of peening from the finished condition after peening. Since surface of the weld toe region is uneven, measurement of the differ-

† Originally published in *JFE GIHO* No. 34 (Aug. 2014), p. 71–76


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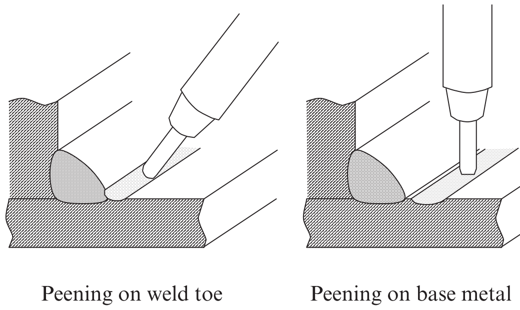


Fig. 1 Hammer peening on base metal

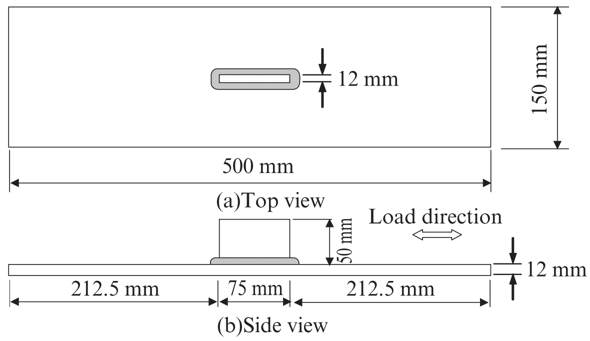


Fig. 2 Specimen for fatigue test

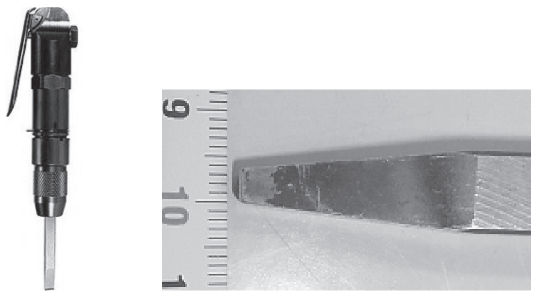


Photo 1 Air tool for hammer peening

ence between the initial shape of the weld toe region before peening and the hammer peening depression shape and detection of the difference is extremely complex. In contrast, with the developed method, impact is applied to the flat base metal, so it is only necessary to measure the hammer peening depression shape after peening, and this is comparatively simple. Thus, as a method for confirming fatigue strength improvement, it is thought that control can be performed based on the depth of the depression due to impact.

The fatigue strength improvement effect of this method was confirmed by fatigue tests of welded joints. The mechanism of introduction of compressive residual stress was verified by a finite element method (FEM) analysis, and the threshold level of the hammer peening depression necessary for fatigue strength improvement was clarified. To further expand the applicability of this method, a mechanized system was also developed, and a quality control method based on the hammer peening depression shape was studied.

2. Fatigue Strength Improvement Effect

The authors have run fatigue tests of welded joints to confirm that effects of the fatigue strength improved by the developed hammer peening on base metal method.

2.1 Fatigue Test Method

The dimensions and specification of the test specimen are shown in **Fig. 2**. SM490Y Steel was used as the base plate and also the out-of-plane gusset plate; 12 mm in thickness, 419 MPa in upper yield strength, 556 MPa in tensile strength, and 22.6% in coefficient of extension. The flat fillet welding between the base plate and the out-of-plane gusset plate is run downward, the welding conditions were 100% CO_2, MXZ200 (1.2φ) flux-cored wire (JIS Z 3313 YFW-C50DM; JIS: Japanese Industrial Standards) in welding consumable, 240 A in current, 30 V in voltage, 40 cm/min in travel speed (10.8 kJ/cm in quantity of input heat), and 6 mm in target weld leg length. The hammer peening to specimens was delivered as shown in Photo 1: the authors made the nib part of the air tool (approx. 90 Hz in frequency, 0.63 MPa in air pressure), flat surface 3 mm × 3 mm with its rounded edges of 0.5 mm in radius. Hammer peening was performed while pressing the air tool nib part vertically onto the base plate near the weld toe. This operation has been performed in ordinary temperature. The depth of the hammer peening depressions should keep under 0.5 mm, in order to prevent being regarded as under-cut, which is a defect of the base metal/weld metal. The reason for making the end of the air tool flat it will be higher efficiency in introducing compressive residual stress into the weld toe region[5].

Sixteen times of series of the fatigue test were performed with stress ratio set at 0 under the following conditions: one as-weld (0 passes of hammer peening specimen) in the nominal loading stress range of 100 MPa and 0 to 4 passes of hammer peening for the three cases of nominal loading stress ranges of 150 MPa, 200 MPa, and 250 MPa. The variation of the number of passes of HP here indicates that of the introduction value of compressive residual stress. The aim in this experiment is to clarify the relationship between the introduction value of compressive stress and fatigue strength.

2.2 Fatigue Test Results and Discussion

Figure 3 shows the results of the fatigue test. The results are shown as a log-log plot with the number of cyclic loading on the horizontal axis and the stress range on the vertical axis. The fatigue strength class curves for the fatigue strength classes from A to E of Japanese Society of Steel Construction (JSSC)[6] are also shown as fatigue strength guidelines. The arrows in Fig. 3 mean

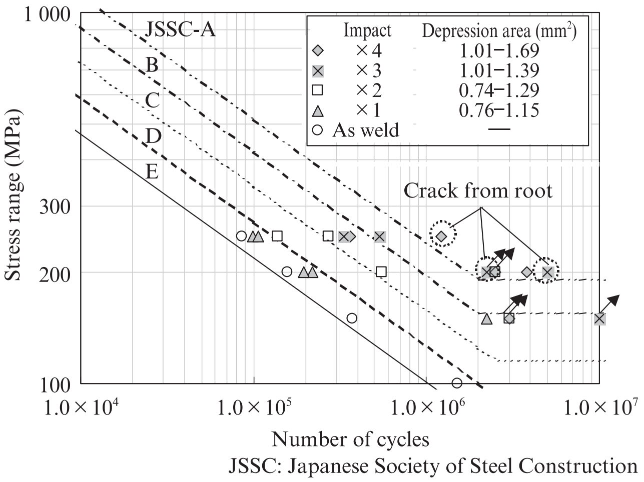


Fig. 3 Fatigue test result

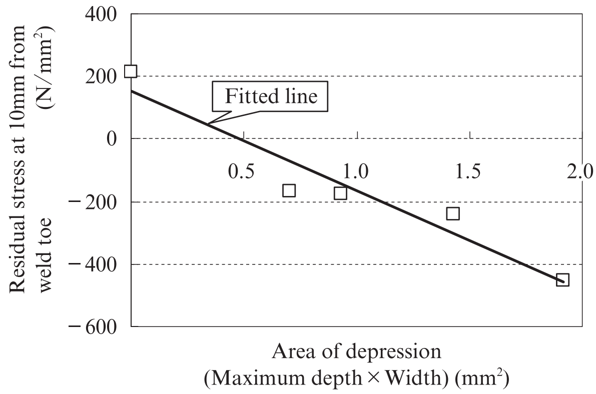


Fig. 4 Relationship between depression area and residual stress

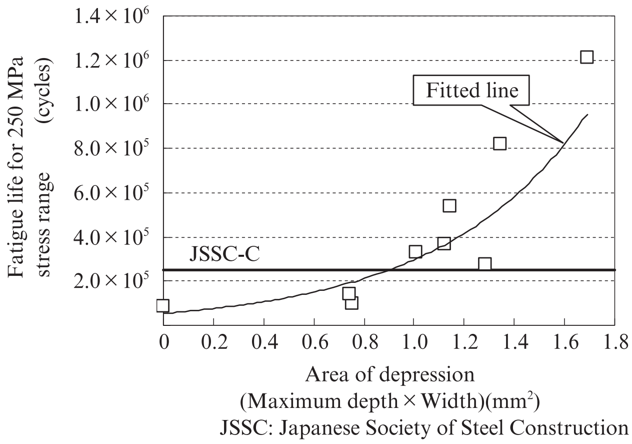


Fig. 5 Relationship between depression area and fatigue life

that fatigue cracks did not occur even on reaching the planned maximum number of cyclic loading (plot points).

The same figure also shows the number of passes of hammer peening (impact) on specimens and the section area of the hammer peening depression for those respective numbers. When the number of passes of HP is 3 or more, the section area of the depression stabilizes at 1 mm^2 or more, and a high fatigue strength improvement effect is obtained. Judging from the lower limit value of the fatigue strength of as-weld specimens plot almost the E fatigue strength class (JSSC-E class), the fatigue strength class is improved by two classes by HP treatment that achieves a section area of depression of 1 mm^2 or more and reaches the JSSC-C class or higher. This suggests, for example, when the stress range is constant at 200 MPa, the life of a JSSC-E class welded joint, in which fatigue fracture occurs at approximately 130 000 cycles, is extended to approximately 490 000 cycles by the developed HP.

The shapes of the hammer peening depressions were measured with a laser displacement gauge before the fatigue tests. The residual stress after HP was also measured by the X-ray diffraction method. **Figure 4** shows the relationship between the section area of the hammer peening depression due to impact and residual stress. The relationship between the section area of hammer peening depression due to impact and the number of cyclic loading until fracture by the fatigue test under the nominal loading stress range of 250 MPa is plotted in **Fig. 5**.

As can be seen from Fig. 4, the introduction value of compressive residual stress increases with increasing of the section area of hammer peening depression due to impact. As indicated in Fig. 5, the number of cyclic loading until fracture also increases with increasing of the depression area, it can be observed that fatigue strength class becomes JSSC-C or higher when the depression area is 1 mm^2 or more.

The results of the authors'experiment demonstrate that it can be governed that the introduction value of compressive residual stress by the section area of hammer peening depressions due to impact, and also the study revealed that the more fatigue strength improves and the larger section area of hammer peening depression due to impact. Moreover, because the fatigue strength of SM490Y achieved the JSSC-C class, that is, an improvement of two fatigue strength classes, as shown in Fig. 3, a section area of hammer peening depression of 1 mm^2 or more is considered to be necessary.

3. Mechanism of Introduction of Compressive Residual Stress

The mechanism of introduction of compressive residual stress by the hammer peening on base metal method was verified by FEM analysis.

3.1 Method of FEM Analysis

The shape of the specimen used in the fatigue test in Chapter 2 was modeled by using 3-dimensional solid elements. The boundary conditions were set so as to

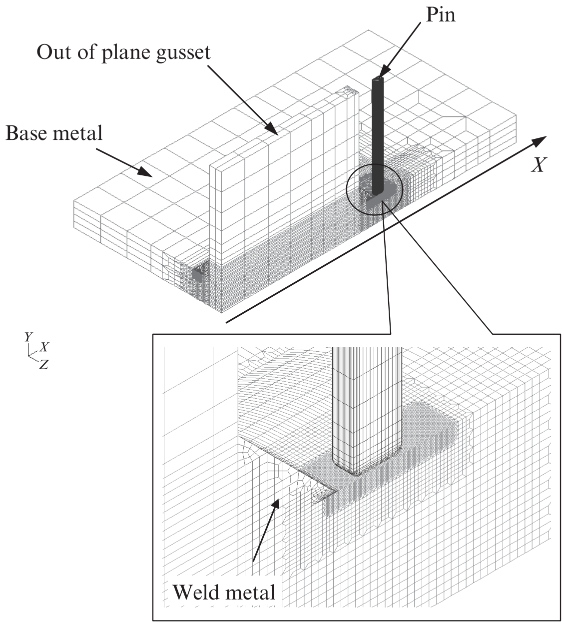


Fig. 6 Model for finite element (FE)-analysis

obtain a 1/4 model (**Fig. 6**). Using Abaqus as the solver, the residual stress after peening near the weld toe was obtained. The distance between the edge of the pin and the weld toe was 0 mm.

In order to simulate the tensile residual stress in the vicinity of the weld toe due to thermal contraction of the weld metal before peening, thermal strain was applied by heating the weld metal to 1 500°C, followed by cooling. To simulate the formation of a hammer peening depression by HP, peening was simulated by statically pushing a pin of the same shape as the air tool nib used in the experiment to a distance of 0.2 mm from the base plate surface and then retracting the pin. The depth of the depression after the pushing and retraction was 0.198 mm.

3.2 Analysis Results and Discussion

The results of the residual stress distribution around the weld toe before and after peening calculated by 3-dimensional FEA are shown in **Fig. 7**. Before peening, tensile residual stress was introduced in the area around the weld toe by thermal contraction of the weld metal. However, after peening, this changed to the compressive stress in virtually the entire range of the hammer peening depression from near the weld toe. Before peening, tensile stress of approximately 400 MPa existed in the weld toe region, but after peening, this region displayed compressive stress of approximately 330 MPa. The same figure also shows plots of the results of X-ray measurements of the residual stress around the hammer peening depression. Since it is difficult to measure the residual stress in the area from the weld toe to the hammer peening depression, a comparison of residual stress was made on the base plate side of the depression. It can be

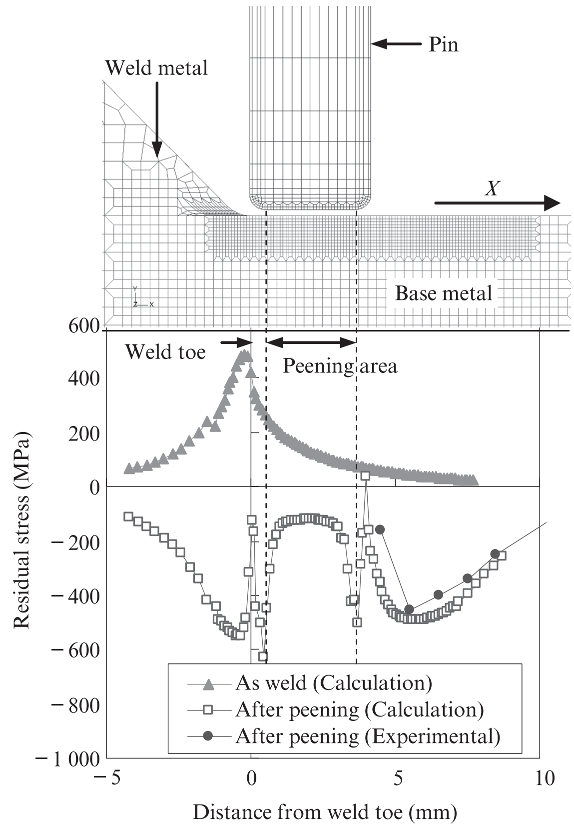


Fig. 7 Residual stress distribution around weld toe

understood that the results of the calculation by 3-dimensional FEA show good agreement with the measured residual stress distribution. From the experimental and FEA results, it was found that the peak of compressive residual stress exists at a position approximately 1 mm from the edge of hammer peening depression.

4. Development of Mechanized System

A mechanized system was developed to further expand the range of application of the hammer peening on base metal method.

4.1 Background of Development and Prototyping of Mechanized System

In conventional HP using an air tool, when performing manual work, it is necessary to apply strong pressure to the base metal side in order to minimize deviations due to vibration. This was a problem, as the HP speed is slow, at 10–20 cm/min, and efficient work is not possible. Furthermore, because the equipment used in this work is treated as a vibratory tool, the daily working time of personnel is also limited. In application to actual structures, mechanized work which does not depend on human strength is desirable when the extension of the peening line is long. Therefore, a prototype of a mechanized system using a welder carriage was trial-manufactured, as shown in **Photo 2**.

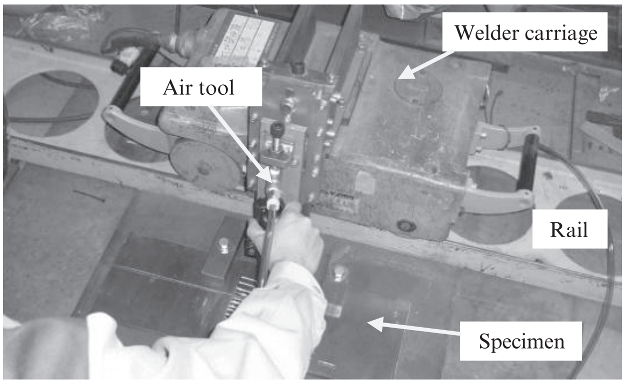


Photo 2 Mechanized system (Prototype model)

In this mechanized system, the air tool is mounted on the welder carriage, which travels on a rail at a fixed speed. The travel speed of the carriage is adjustable within the range of 0–120 cm/min.

4.2 Compressive Residual Stress Introduction Effect

The compressive residual stress introduction effect when using the mechanized system was confirmed. Vertical peening was performed on a flat plate at a carriage travel speed of 60 cm/min. The results when peening was performed one time and two times each with two test specimens were compared.

Figure 8 shows the relationship between the number of passes of hammer peening and compressive residual strain. Here, the horizontal axis shows the distance from the depression peak, and the vertical axis shows the introduced compressive residual strain. If the number of passes of hammer peening is increased, the compressive residual strain generated in the weld also increases, and the increase also becomes larger at points closer to the depression. It is possible to introduce compressive residual stress even with one pass of hammer peening, but one-pass HP can result in a certain amount of waviness of the treated surface. Therefore, to obtain a stable effect, it is considered necessary to perform a minimum of two hammer peening passes (1 round trip).

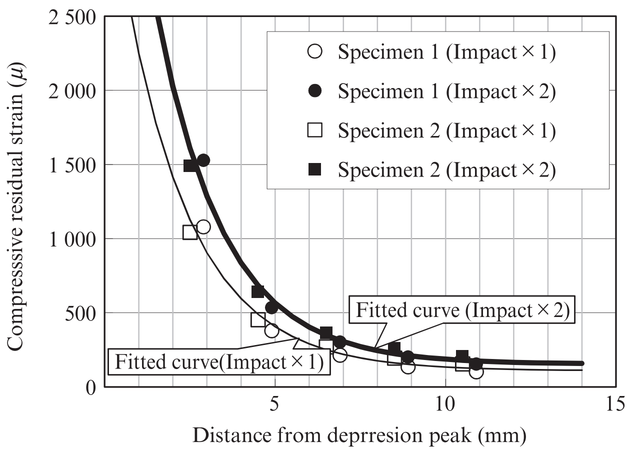


Fig. 8 Compressive residual strain for number of impacts

4.3 Fatigue Test

The fact that a stable fatigue strength improvement effect can also be obtained by peening when using the developed mechanized system was confirmed by a fatigue test. The fatigue test specimen was a non-load-carrying cruciform welded joint, as shown in **Fig. 9**. Fatigue tests were performed with four specimens. The material was SM490YA, and the fillet welding conditions were leg length 6 mm, welding consumable MXZ200 (1.2φ), current 240 A, voltage 30 V, and speed approximately 35–40 cm/min. The test was performed at a vibration frequency of 8 Hz using a fatigue testing machine with a maximum tensile load of 200 kN. As the load amplitude, the load was set in one-side amplitude so that the minimum value of tensile stress becomes 5 MPa. With these test specimens, HP was performed on the base metal under the condition of two passes of HP by automatic travel at the speed of 90 cm/min, and a target distance between the weld toe and the hammer peen-

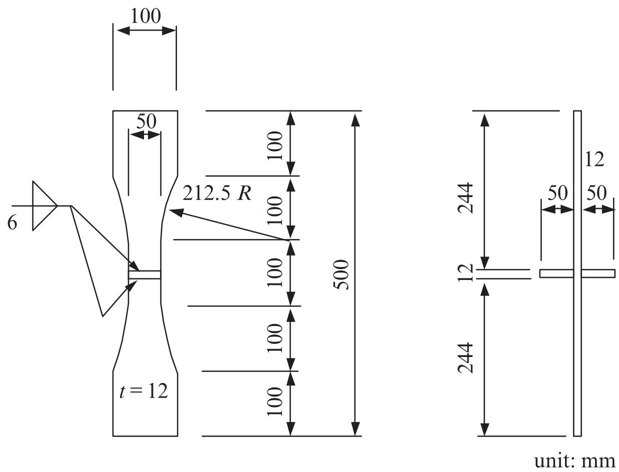


Fig. 9 Specimen for fatigue test

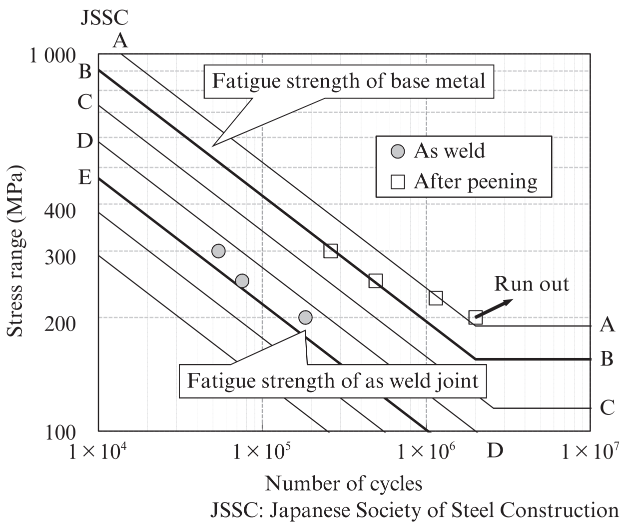


Fig. 10 Fatigue test result

ing depressions of 2.5 mm.

The fatigue test results are shown in **Fig. 10**. In comparison with the as-weld condition, an improvement of two JSSC fatigue strength classes was confirmed when the stress range was 250–300 MPa, and a four class improvement was observed when the stress range was less than 200 MPa.

4.4 Control Value of Hammer Peening Depression

The measurements of the hammer peening depression shape of the specimens in Section 4.3 were performed with a laser displacement gauge before the fatigue test. Here, the performance of the laser displacement gauge is pitch 50 μm, height resolution 1 μm, and measurement error 20 μm.

Table 1 summarizes the local shape of the hammer peening depressions of the fatigue test specimens. Here, the depth of depression due to impact *h* means the height of the deepest part of the depression measured from the steel plate surface, the width of the impact area *b* is the length where the depression crosses the plane of the plate surface, and the distance from the weld toe *d* is the length between the weld toe and the peak of the depression on the toe side.

With all specimens, the minimum value of the depth *h* was 0.22–0.25 mm. It is conjectured that the same fatigue strength improvement effect as in this research can be obtained by setting 0.25 mm, which was the maximum value of *h*, as a guideline for the depth of depression due to impact.

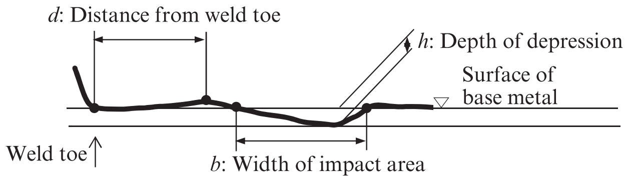
In this test, peening was performed with a target value of 2.5 mm as the distance from the weld toe *d*. In contrast to this, the maximum value of distance *d* was 2.55–2.95 mm with all test specimens. It is necessary to perform peening as close to the weld bead as possible in order to obtain the fatigue strength improvement effect. However, in actual welding, some waviness exists in the bead, and even excluding discontinuities in the weld line, irregularities on the order of 2 mm are conceivable. If large protrusions, like those which occur at breaks in the weld line (where welding was discontinued and then resumed) are removed in advance with a grinder, it is considered possible to perform peening with the mechanized system, even when the distance from the weld toe is set to a control value of 2.5 mm.

4.5 Expansion of Application to Actual Structures

For more efficient HP in actual structures, a mechanized system with 2 air tools was developed (**Photo 3**). By performing HP simultaneously on the weld lines on both sides of a longitudinal rib, it is easier to achieve a balance of reaction than in one-side peening, and stable peening of long extensions is also possible. The reason for the inclination of the hammer peening depressions shown in Table 1 is due to the fact that peening is performed with the air tool slightly inclined, as shown in Photo 3.

Table 1 Local shape of fatigue test specimen after peening

Specimen number	Stress range (MPa)	Number of cycles ($\times 10^3$)	*d* max. (mm)	*h* min. (mm)	*b* min. (mm)	$h \times b$ min. (mm^2)
1	300	260	2.55	0.24	2.45	0.70
2	250	490	2.55	0.25	2.44	0.70
3	225	1 140	2.95	0.22	2.06	0.52
4	200	Run out	2.80	0.24	2.20	0.64



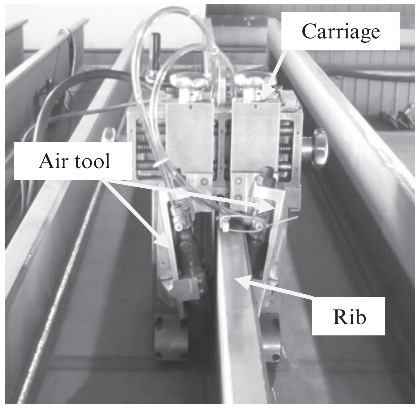


Photo 3 Mechanized system for longitudinal rib

5. Conclusion

A new peening method, hammer peening on base metal, which improves the fatigue strength of welded joints was developed. By applying impact to the base metal near the weld toe, it is possible to improve fatigue strength by two or more JSSC fatigue strength classes in comparison with as-weld specimens (JSSC: Japan Society of Steel Construction). An FEM analysis confirmed that strong compressive residual stress can be introduced in the weld toe region and clarified the threshold value of the hammer peening depression shape required for improvement of fatigue strength. A mechanized system using a self-propelled carriage was also developed in order to realize more efficient hammer peening.

It is thought that a more practical control method for this HP technology can be established by providing support based on further analytic and experimental research.

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