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Paper:

Mechanoluminescent Testing as an Efficient Inspection Technique for the Management of Infrastructures

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This paper reports on the mechanoluminescence inspection technology we have developed and its applications. The inspection technology is expected to identify deterioration and damage, such as fatigue cracks developed on steel members of steel structures, using particular mechanoluminescence (ML) phenomenon. In field testing at an urban highway bridge currently in service, fatigue cracks in steel box girders were successfully detected using the proposed technology. In addition, using a conventional crack detection method known as magnetic particle inspection (MT), similar results were obtained in terms of crack judgment, suggesting that the reliability of the ML method is equivalent to that of the MT method. An advantage of the ML inspection method is that it does not require removing corrosion protection coating, saving labor that is necessary in the MT method. The field testing also examined the possibility of evaluating precautionary measures (repair) as another application of the ML technique. As a result, the ML technique quantitatively evaluated that detected cracking had been properly repaired (removed). It is expected that the ML technique will contribute to effective maintenance and management of infrastructures from the perspective of preventive maintenance.

Keywords: mechanoluminescence, inspection, fatigue cracks, steel bridge, infrastructure

1. Introduction

Structures in roads, bridges, railways, and bays are essential social infrastructure in our lives. However, we cannot use such social infrastructure permanently beyond their lifetimes. In particular, structures with long service life suffer various types of damage, such as corrosion, fatigue, and concrete deterioration [1–4]. Such damage will proceed continuously without proper treatment and sometimes leads to hazardous situations, including collapse and physical injury. Constant maintenance is required for long-term safe and secure service of infrastructures.

In Japan, many highways, tunnels, and bridges were constructed in the rapid economic growth period from the 1960s–1970s. It has been pointed out that these structures will deteriorate more in the near future, 10–20 years, with high accident risks. In addition, an increase in maintenance costs to suppress these risks is also concerning. We are forced to manage important infrastructure with limited budgets. An effective measure to extend infrastructure service life is preventive maintenance. This is a management method for effectively extending infrastructure lives by detecting and repairing defects before severe damage occurs, resulting in smaller economic burdens. Today, new techniques related to preventive maintenance are being developed and drawing attention [5–7].

With this in mind, the authors have developed a new inspection technology using a luminescence phenomenon called "mechanoluminescence" (ML) [8]. This technology is expected to detect damage such as fatigue crack without destruction. The authors have been involved in a wide range of research and development from fundamental research on ML materials to their applications [9–11]. The novel ML material developed by the authors emits light when an external mechanical stimulus (strain), such as tension and bending, is applied (**Fig. 1**). In addition, the obtained ML intensity distribution correlates well with the stress distribution of actual structures in the elastic range, allowing for quantitative stress analysis. In other words, a sensor using the ML material can function as a mechanical sensor. A sensor using the ML material (ML sensor) can easily be created by applying an ML paint coating to a test object with a spray. When there is damage, such as fatigue crack or stress concentration, ML is generated from the ML sensor (coating film) by an external stimulus [12]. This ML detection and visualization enables identification of latent damage and deterioration in an object. In addition, an ML sensor can easily be applied to a larger area and this characteristic is significantly different from point sensors, such as a widespread strain gauge. It is expected that this ML technology will considerably contribute to the preventive maintenance of structures as an effective

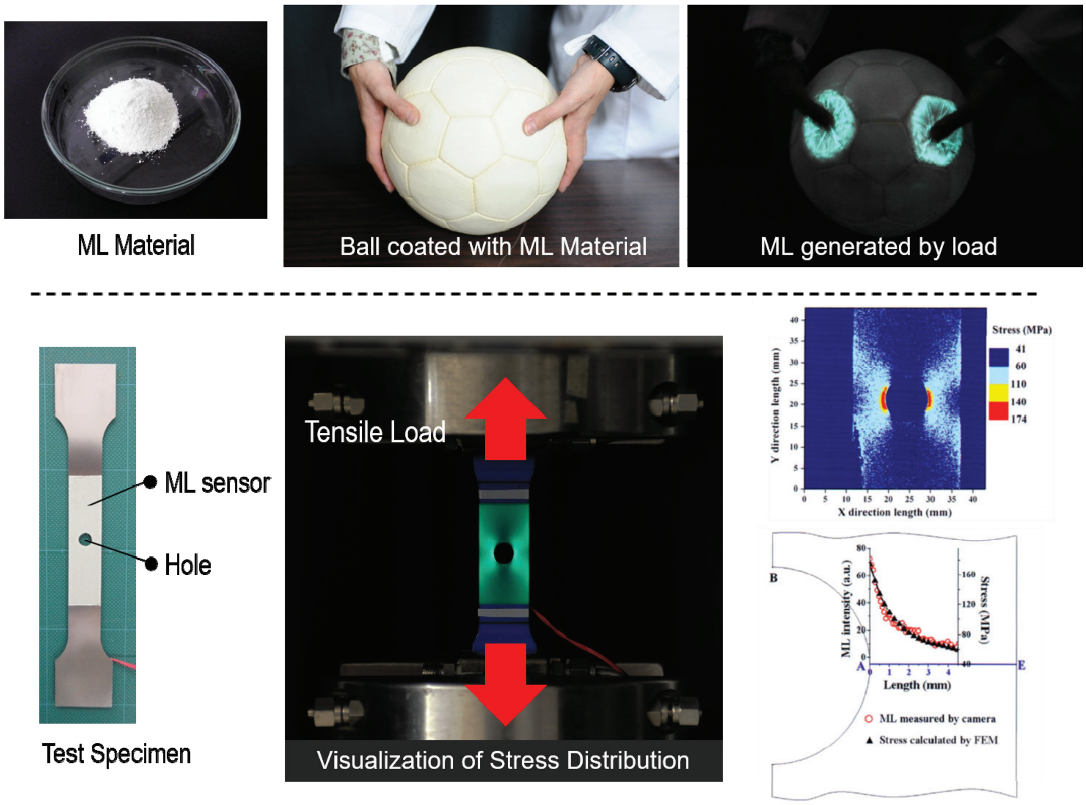

Fig. 1. Stress distribution can be visualized using ML materials.

and economic non-destructive inspection method.

This paper reports an application case of the ML inspection technique to infrastructures in service. The objective of the field testing was to investigate the detection capability of the technique for fatigue cracks in actual bridges and study the advantage of the ML inspection method, comparing the technique with the existing magnetic particle inspection (MT) technique. Urban highway bridges with steel box girders were selected as the primary application case and relatively damage-prone structure portions were examined (**Fig. 2**). As another ML technique application case, field testing investigated the capability of detecting cracks remaining after shallow fatigue crack removal processing with a grinder.

2. Experimental Procedures

2.1. Field Testing and Object Inspection

Field testing was performed within the steel box girder on the Urban Expressway (UE), Fukuoka City, Japan (**Figs. 2(a)** and **(b)**). The UE began service in 1980 and is a relatively new urban expressway in Japan. It has a total route length of 56.8 km and 180,000 vehicles pass through it on average per day (2015). The majority of the UE consists of road bridges built over existing national roads. The target steel box girder for applied ML field testing was one generally used in urban elevated bridges. The steel box girder consists of a flange, rib, diaphragm, and stiffener. These steel members are generally coated for corrosion protection.

Preliminary visual inspection results on the box girder showed more than 300 cracks in the corrosion-proof coating (coating cracks) in the relevant section (two spans). In particular, many coating cracks were found at the turn around weld at the intersection of the U rib and the cross rib (**Figs. 2(c)** and **(d)**). It is conventionally known that complex deformation tends to occur locally owing to vehicle traffic around the intersection parts, which are subject to relatively higher stress concentration that leads to fatigue cracks [14, 15]. Therefore, the authors selected the intersection of the U rib and the lateral rib, where fatigue cracks tend to occur, as the inspection target of this field testing. In principle, coating cracks do not necessary mean fatigue cracks. It is difficult to judge the presence of latent fatigue cracks under coating cracks detected by visual inspection. The authors sought to judge the presence of fatigue cracks under corrosion-proof coating using the ML inspection technology.

2.2. ML Inspection Procedures

Figure 3 shows ML inspection procedures. The ML inspection method is mainly composed of two processes: ML sensor implementation and ML measurement. The authors recently succeeded in increasing the sensitivity of defect-controlled $SrAl_2O_4$:Eu powder, an original ML material, on the responsiveness in the small-strain range. The experiments in the current study used the new

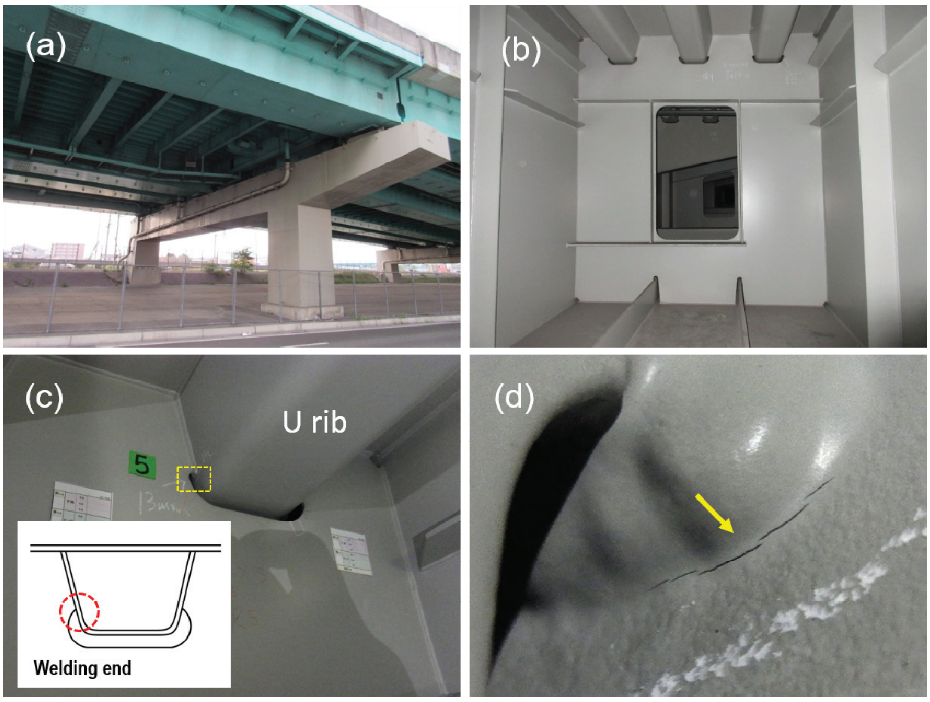

Fig. 2. (a) Typical photo image of a highway bridge with box girders and (b) the inside of a steel box girder. (c) Test target area in this study. Inset shows a schematic illustration of a U rib. The rib connection area is marked with a red-dashed circle. (d) Enlarged image of the frame shown in (c). The film cracking is indicated with a yellow arrow.

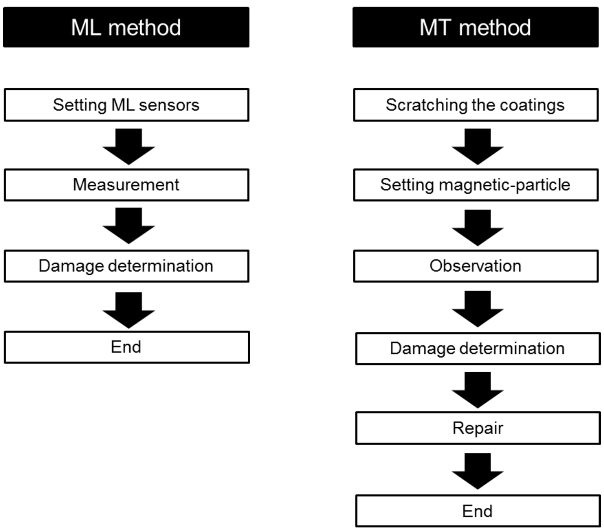

Fig. 3. Procedure of (a) ML and (b) MT inspection methods.

high-sensitivity ML material. It was demonstrated that the material emits light with an intensity of more than 100 mcd/m^2 when strained 1000 μst (a five times increase compared to conventional materials). In the implementation process, hardening resin paint containing the high-sensitivity ML material was applied around the target rib intersection over the corrosion-proof coating film at an area of $\sim 10 \times 10$ cm^2. The paint used in this test is usually effective at room-temperature on the resin hardening. However, a 1-h heating and drying process with a lamp was added to complete hardening because the test was held during midwinter and environmental temperature was low. This resulted in an ML sensor with a film thickness of about 60 μm. For the testing, 12 coating cracks (out of 300 total) at the rib intersections were selected and the ML sensors were applied to each location. A CCD camera system developed by the authors and a commercial video camera (iVIS HF G20, Canon) were used for ML measurement. Luminescence can be recorded as still and moving images with this measurement setup. For the purpose of quantitative evaluation using the implemented ML sensor, a process of light irradiation at specific time intervals was needed. A blue LEDs fixed in front of the camera lens was used as the light source. The LEDs were arranged in a ring shape coaxially with the camera lens to irradiate to the entire measurement object. For several minutes, light was repeatedly emitted for 1 s followed by a 9-s pause to record images with the camera. As discussed above, a certain external stimulus (load) is required to generate ML. In the testing, loads were applied by vehicles driving on the floor panel above the box girders (at random) and hammering at the U rib (on purpose). Strain that was generated around the intersection during the test was measured using a strain gauge. A fatigue crack in the test object was identified by analyzing recorded images.

2.3. Conventional MT Method

The authors additionally used the MT method that is a representative conventional technique to detect cracks to

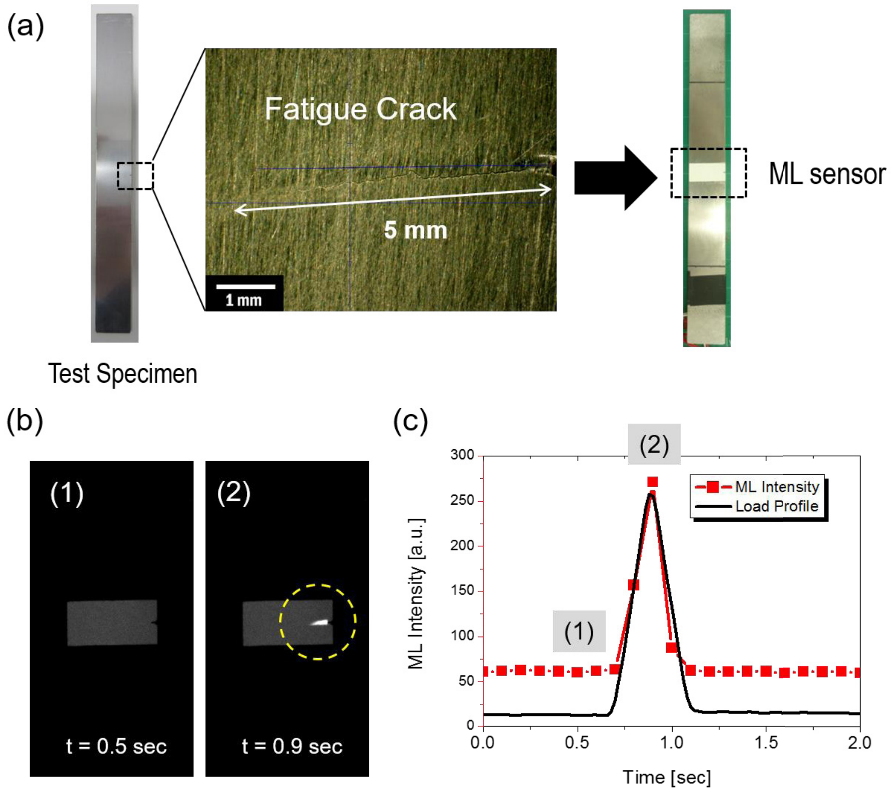

Fig. 4. Results of a preliminary experiment to visualize fatigue cracks. (a) Test specimen with a fatigue crack. (b) Images obtained at no-load (1) and onload (2). (c) Time-dependent luminescent intensity in image (2) along with the load profile of tensile test.

evaluate the validity of crack judgment by the ML inspection method. The MT method was performed by personnel who are qualified non-destructive testing (MT2, JIS Z 2305) with the same inspection conditions and systems as usual. After the ML inspection was completed, MT inspection was conducted for the same part following the procedures in **Fig. 3**. During the inspection, the corrosion-proof coating (including the ML sensor) had to be completely removed with a grinder or other instruments to effectively apply magnetic powder around the damaged portion. The magnetic powder used in the test was green fluorescent, indicating damage such as cracks as green patterns. The visualized crack patterns were recorded as image data. The authors compared results of both methods to evaluate the validity of judgment results based on the ML inspection method. After finishing the MT method, repair coating for corrosion proofing was applied to all detached parts.

3. Results and Discussion

3.1. Preliminary Validation Experiments in Laboratory

Before starting field testing, preliminary experiments on the visualization of fatigue cracks were performed in a laboratory. The experiments used specimens with fatigue cracks of approximately 5 mm in length and ML sensors were applied to cover the fatigue cracks (**Fig. 4(a)**. Tensile testing was performed using this specimen. **Fig. 4(b)** shows an example of an image obtained with the CCD camera system. Image (1) was obtained when no loads were applied, while Image (2) was obtained when loads were applied. Luminescence was detected on the right side of Image (2); the length and position of the luminescence correlate well with those of the fatigue crack. **Fig. 4(c)** shows chronological changes of luminescence intensity and load profiles during the tensile testing. The figure shows that luminescence in Image (2) resulted from the external load and thus was mechanoluminescence. The preliminary experiments indicated that fatigue cracks can be detected and identified by measuring mechanoluminescence from the ML sensor.

3.2. ML Detection Example

This section describes field testing results. Firstly, an example of actual ML detection in the testing is presented. **Fig. 5** shows measurement results using the CCD camera system at an inspection point (denoted as T1). **Fig. 5(a)** is an image in a clear visual field around the rib intersection with the ML sensor implemented. **Fig. 5(b)** presents an image obtained when a vehicle load was applied. Note that the timing of loading owing to passing vehicles can be determined by the concurrent strain measurement. ML can be observed around the weld joint in the image. This luminescence is similar to that observed in the preliminary

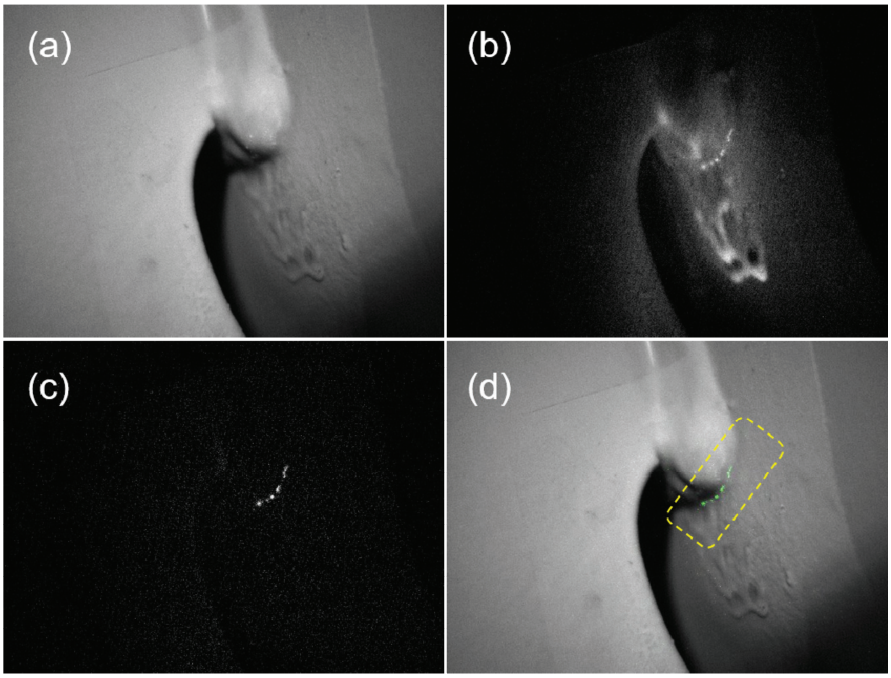

Fig. 5. Typical images obtained by ML test for T1. (a) Bright-field image of test object. (b) ML image (on-load). (c) Image after eliminating noise components. (d) Composite image made by (a) and (c).

validation experiment (**Fig. 4(b)**), suggesting the presence of a fatigue crack. Images obtained during ML measurement usually contain a luminescence component called "afterglow" as noise, which is sometimes difficult to distinguish from ML. Therefore, **Fig. 5(c)** shows the extracted ML component by eliminating noise components through image processing. The figure includes discontinuous half-moon luminescence. In order to clarify ML, a composite image (**Fig. 5(d)**) was created by superposing the ML image in **Fig. 5(c)** on the image in clear visual field in **Fig. 5(a)**. In the figure, ML generated around the weld joint where a coating crack had been found, suggesting that the fatigue crack was due to abnormal stress concentration (generated fatigue crack). Similar results were obtained at several other inspection points.

3.3. Comparison between ML and MT Inspection

In order to evaluate the fatigue crack judgment based on ML images, MT inspection was performed after ML inspection. **Fig. 6(a)** shows the results of ML and MT inspections for the testing target T1. Here, the ML image on the left is the same as the composite image in **Fig. 5(d)**. In the MT image (right), a crack is shown in the linear magnetic powder pattern around the weld joint (yellow dashed frame). The position of the crack corresponds well to the position of ML in the ML image (left). In other words, the ML visualizes a latent crack inside the corrosion-proof coating, suggesting that the crack judgment of the ML inspection was valid.

Comparison results of both inspection methods with another test object (T2) are shown in **Fig. 6(b)**. In this case, no ML was observed in ML inspection, and no magnetic powder patterns that can be attributed to a fatigue crack were observed in MT inspection. In the two cases (T1 and T2), results of the two inspection methods accorded, indicating the high detection accuracy of the ML

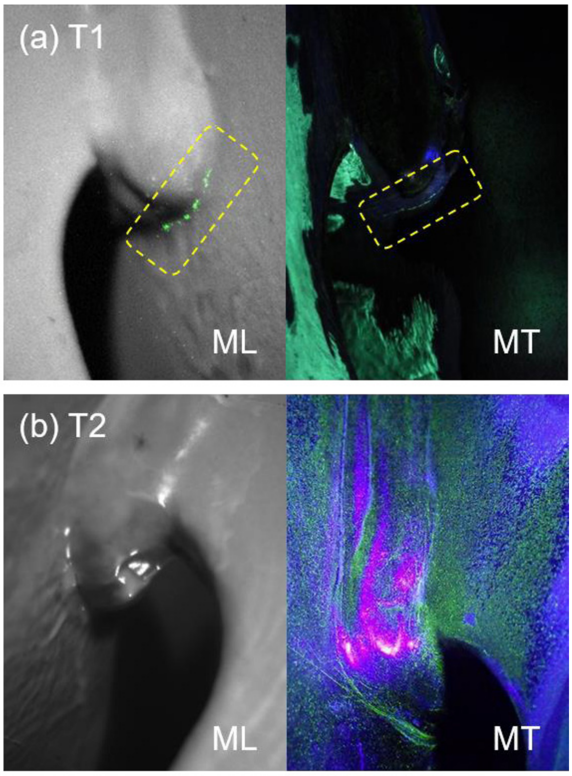

Fig. 6. Comparison of results by ML method (left) with MT method (right). (a) T1 and (b) T2.

Table 1. Results of ML and MT tests for the detection of damage.

	The number of targets		ML	MT
Damage determination	3	1	Detected	Detected
		2	Detected	N/A
	9		N/A	N/A
Total test targets	12			

inspection technology.

Meanwhile, judgment results of the two inspection methods differed in some cases. In such cases, linear (discontinuous) ML that suggests the presence of a crack can be observed in ML images, but no magnetic powder patterns were observed. The authors considered there were fatigue cracks of several mm (less than 10 mm) based on ML images. The main reasons why cracks could not be found by MT are deemed to be 1) it was difficult to find and judge cracks because of residual coating since corrosion-proof coating cannot readily be removed in the complex shapes of the inspection object and 2) it is difficult to identify small cracks by means of visual inspection (or on images). These are technological limitations of the MT method in actual sites. In contrast to the MT method, the ML inspection method is advantageous in that the corrosion-proof coating need not be removed and small defects, such as cracks, can easily be detected as a form of luminescence as long as there is variation of stress (strain). **Table 1** shows the results of both inspection methods.

In addition, the economic advantage of the ML method is discussed. The authors presume that inspection using this technology can be implemented with lower costs compared to conventional MT technology. One reason is the smaller number of procedures of this technology. The MT technology requires two processes: removal of corrosion-proof coating and repainting after inspection. In general, the detection efficiency in MT method is low because cracks were often not found after the inspection involving coating removal. In addition, there are vast number of target points (coating cracks) which were found in the visual inspection phase. It is impossible to inspect all of these points considering the amount of tasks, time required for tasks, and cost. Another reason is that removal of corrosion-proof coating is a destructive process that can lead to unexpected deterioration while repair paint is performed. In contrast to the MT method, the ML method is only composed of non-destructive processes; ML paint is applied over the corrosion-proof coating to measure luminescence. The method does not require repair painting and long inspection time, reducing costs for maintenance. As discussed in the following sections, the use of commercial devices and hammering inspection increases the inspection efficiency, significantly contributing to cost reduction.

3.4. Inspection Using Digital Video Camera

The ML inspection method described above used a high-sensitivity CCD camera system. The authors subsequently tried ML inspection using a commercial digital video camera. During the inspection, full-color moving images were recorded instead of still images. The highest sensitivity of the system was maintained by fixing the exposure time and sensitivity. The automatic mode was avoided because detection of luminescence could become difficult with varied conditions such as exposure time. Inspection results confirmed ML around the welded joint when loads were generated by passing vehicles. In addition, ML was detected for other testing objects with the commercial camera. It was shown that inspection can be carried out using commercial cameras instead of high-sensitivity measurement cameras. This is another benefit of the ML inspection method.

3.5. Impact Inspection

Disadvantages of the ML inspection method include that the task efficiency depends on irregular and uncertain vehicle driving frequency. It is expected that it will take a longer time to inspect one test object when testing is performed at night with less driving vehicles than test cases performed during the daytime. The utility value of the ML inspection method would increase if it were independent of vehicle driving frequency and inspection time of day. Therefore, the authors propose hammering (impact) inspection as a solution. We investigated detection or visualization of cracks by hammering in a similar method as that with passing vehicles. The CCD camera system was used for measurement. The U rib portion opposite to the camera was hit by a hammer. Testing results showed ML around the weld joint when hammering. The position of luminescence correlated well with the position of ML in the case with driving vehicles, indicating that the hammering inspection results were equivalent to those of the inspection with passing vehicles. The hammering method is considered to be very effective for regular inspection because it is independent of driving vehicles and operation time of day.

3.6. Evaluation of Preventive Measures

Some fatigue cracks found in the ML inspection can easily be removed using a grinder or similar methods because short cracks are expected to have shallow depth. Steel structures can effectively and economically be maintained if damage, such as cracks, is detected by the above ML inspection method and promptly addressed. However, it is problematic that there are no criteria nor findings or technology to judge the effectiveness of processing and repair. With this in mind, it was considered that the ML inspection technique could evaluate the effects. Therefore, three cracks detected by the preceding ML inspection were removed with a grinder and then it was confirmed that there were no magnetic powder patterns due to cracks using the MT technique. Following this, an ML

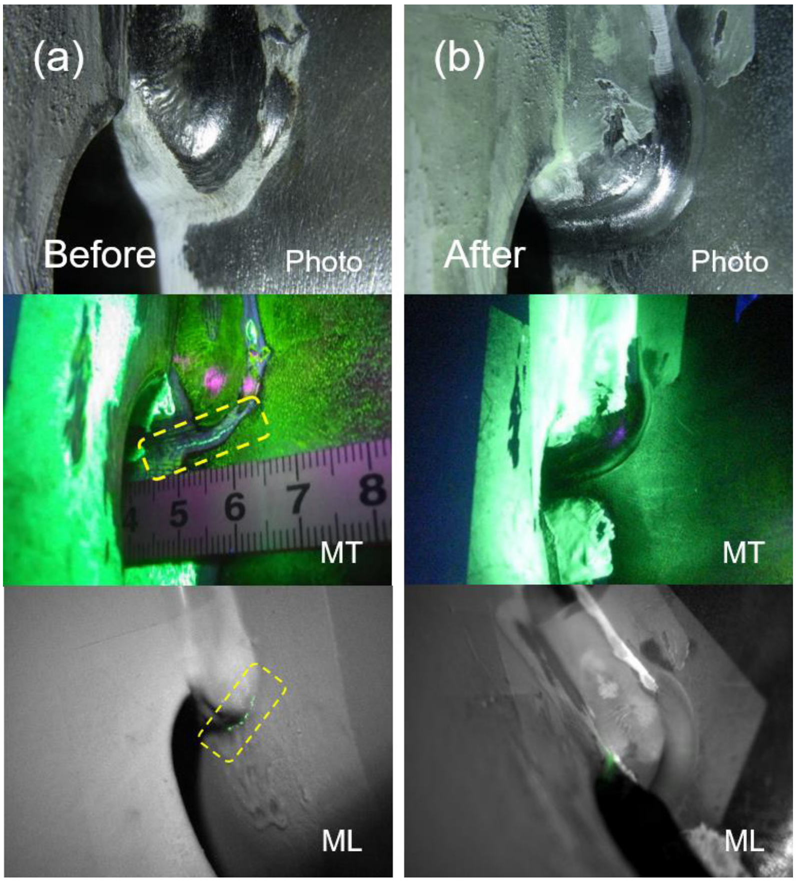

Fig. 7. Photos of MT and ML results for T1 (a) before and (b) after the grind process at the welding joint.

sensor was implemented and ML measurement was performed again to compare ML images before and after the processing.

Investigation results of T1 were taken as an example. **Fig. 7** (top) presents pictures taken before and after crack removal using a grinder. During the process, the shape of the weld joint improved. MT inspection results obtained before and after the processing (**Fig. 7**, middle) show a magnetic powder pattern corresponding to a crack before the grinder processing, but not after the grinder processing. Therefore, the crack was removed based on the MT judgment criteria.

Figure 7 (bottom) shows ML inspection results taken by the CCD camera system before and after the grinding work. These are composite images superimposing the ML images on the images in a clear visual field. Linear ML reflecting a crack observed before grinding work was removed after the processing and changed into a weak, broad luminescence image. The results indicate that removal of cracks can be judged using the ML inspection technique. The weak mechanoluminescence after processing resulted from stress concentration. Stress tends to concentrate at the target point (weld joint). ML that had been clearly observed at the weld joint was removed after processing in the other two points and changed into weak, broad luminescence distribution. From the above, the authors demonstrated that the ML technique can properly evaluate the processing quality of grinder work to remove a fatigue crack.

4. Conclusions

This paper reported application cases of the ML inspection method developed by the authors to steel box girders in an urban expressway bridge. The field testing demonstrated that damage to steel members, such as fatigue cracks, can be visualized. With regard to crack detection judgment, experiments showed (1) the crack detectability is no less than the existing MT method (all cracks detected by the MT method can be detected by the ML method). In addition, (2) the ML method detected damage that could not be detected by the MT method, indicating that the ML method is reliable and exhaustive. Furthermore, (3) complete removal of a crack was confirmed by the ML method after crack removal as a preventive measure. Therefore, the ML method can be used for evaluating processing quality of preventive measures and repair. The ML method can be applied without removing the corrosion-proof coating, reducing costs required for inspection. However, some issues remain in the case of the ML method. For example, the number of inspection cases must be increased to increase evaluation reliability in relation to crack detection accuracy, criteria to judge the necessity of repair for detected cracks must be formulated, and the durability of the implemented sensor coating film must be examined. The authors wish to evolve the ML technique by repeating field testing to utilize it for preventive maintenance.

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