Application of Laser Speckle Strain Measurement to Weld Monitoring

The possibility of in-situ measurement of dynamic strains is examined for gas tungsten arc welding

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ABSTRACT. The laser speckle method has been applied to the measurement of dynamic strains at high temperature in welding. The method depends on the fact that the speckle pattern formed by the scattered light from an object surface under laser illumination deforms with a specific relation to the surface strains on the object.

The strains on the bottom surface of a steel plate were measured by the speckle method while a GTA traversed on top of it. Qualitatively reasonable strain behavior was observed except for a period when the arc was in the vicinity of the measuring point. In order to understand the reasons behind the problem, simple model experiments were carried out to see the effects of strains and rigid body motions on the speckle patterns.

The results indicate that a high rate of strain change as well as some components of the rigid body motions of the specimen are likely to be the causes of the difficulty.

Introduction

Laser speckles are random bright and dark patterns caused by interference of the scattered light from the object surface illuminated by a laser. Since the speckle patterns change according to the strain or movement of the object surface with a specific relation (Ref. 1), a series of techniques generally called speckle interferometry have been developed to extract information about the object's surface from the speckles (Ref. 2). One of these methods, developed by Yamaguchi, *et al.* (Refs. 3, 4), enables us to measure the local in-plane strain on the surface of an object almost instantaneously with high accuracy. It has been often used for measurement of the mechanical properties of materials substituting for strain gauges. If it can be applied to strain measurement at high temperature, such as in the welded zone where dynamic strains are caused by a local heat input, strains at high temperature, which have been estimated only by numerical analysis, will be quantified, and the mechanisms of defect generation at high temperature, such as hot cracking in welds, may be clarified.

In order to apply the laser speckle method to welding, however, the following problems need to be considered. One class of problems arises from the welding environment, which may hinder accurate measurement of speckle pattern. These are:

1) Fluctuation of the surrounding atmosphere due to convection.

2) Intense emission from the welding arc.

3) Decrease of the surface reflectance by the formation of oxidized film.

The other class of problems arises from the so-called decorrelation of speckle patterns (Ref. 5). Since one needs to trace the motion of speckles, topological changes in speckle patterns, which can be caused by excessive motion or deformation of the object surface, must be controlled.

In our experiments, the effect of gas fluctuation has been minimized by measuring the strains on the bottom surface of a specimen while a gas tungsten arc (GTA) weld is applied to the top surface. Interference by the emission from the arc and the low reflectance by oxidation can be overcome by employing a high-power laser for illumination and narrow bandpass filters tuned to the laser wavelength in the receiving optics.

In the quasi-static strain measurement at high temperature (Refs. 6, 7), strain has been measured up to 573 K in the atmosphere and measured up to 873 K in vacuum. Therefore, in principle we can expect to apply this method for measurement of dynamic strains in welds once these problems are solved.

In the following, the principle of the laser speckle strain measurement is briefly introduced first. Then, an experiment to apply the technique to GTA welding of a steel plate is described. The result will indicate qualitatively reasonable strain behavior except some difficulties when the arc is near the measuring spot. Various factors suspected to be the reasons for the difficulties, such as excessive motion or deformation of the specimen, as well as the high strain rate due to rapid heating and cooling, will be examined with simplified model experiments. The importance of some measurement parameters, such as the diame-

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KEY WORDS

Strain Measurement
Laser Speckle Method
Speckle Pattern
Dynamic Strain
Sampling Rate
Spot Diameter
Rigid Body Motion
Cross Correlation
Image Sensor
Thermal Stress

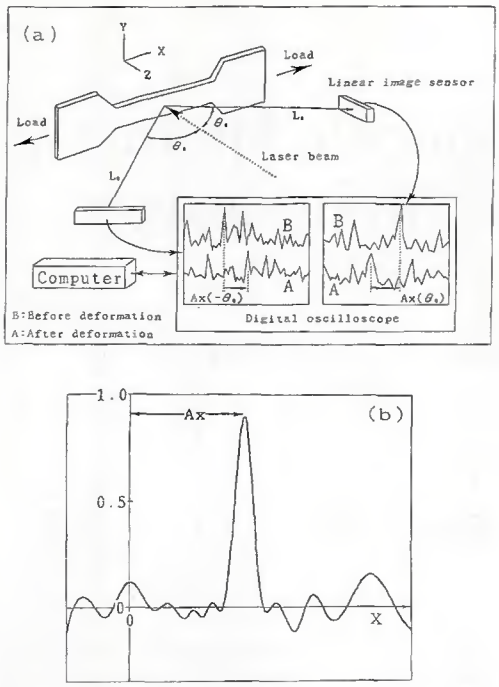

Fig. 1 — Schematic illustration of the laser speckle strain measurement. A — Outline of the method; B — an example of cross-correlation function.

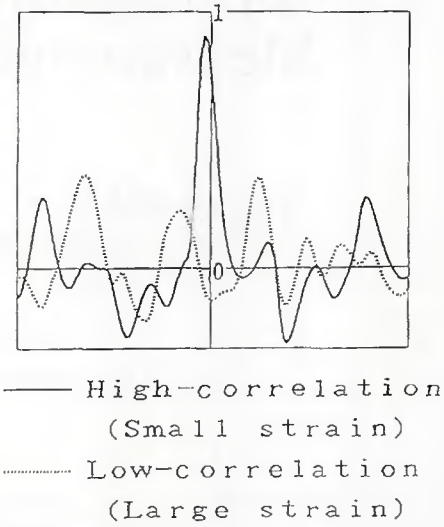

Fig. 2 — Examples of cross-correlation function with high and low correlation.

ter of a laser beam and the sampling rate (Ref. 8) to record the speckle patterns, will be clarified.

Principle of the Laser Speckle Method

Figure 1 shows a schematic illustration of the laser speckle strain measurement. A laser beam illuminates the surface of a specimen, and the scattered light forms a random bright and dark pattern called laser speckle on the linear image sensors.

The speckle pattern has a reciprocal relation with the in-plane deformation of the object surface, *i.e.*, the speckle pattern expands when the object surface contracts and vice versa. This pattern, however, also changes by the rigid body motion, and therefore only the change in the pattern by the strain must be taken out. For this purpose, two image sensors are placed symmetrically against the point for measurement. The speckle pattern before and after deformation of the specimen on each sensor is measured. Then, the amount of the shift of the pattern on each sensor $A_x(\theta_0)$ and $A_x(-\theta_0)$ can be obtained by calculating the shift in the peak position of the cross-correlation function as shown in Fig. 1B between the patterns before and after the deformation, as will be described later. The lateral strain in the X-direction can be obtained by taking the difference between the two shifts, which corresponds to the degree of expansion or contraction of the speckle pattern. The surface strain of the specimen in the direction of the row of the photo-sensitive elements of the sensor (in the X-Z plane) can be measured by the layout in the figure. Since the speckle pattern usually tends to lose similarity with large applied load, the height of the correlation peak tends to decrease with a large strain, as shown in Fig. 2.

Formulas to convert the speckle patterns to strains are shown below (Refs. 1, 6).

$$\Delta A_x = A_x(\theta_0) - A_x(-\theta_0) = -2L_0\varepsilon_x \tan\theta_0 - 2a_z \sin\theta_0 \qquad (1)$$

Where, $A_x(\theta_0)$ and $A_x(-\theta_0)$ are the shifts of patterns on the two sensors. L_0 and θ_0 are the distances between the sensor and the measuring point on the object surface, and the angle of sensing, respectively. ε_x and a_z are the strain in the X-direction and the normal movement of the specimen in the thickness direction Z.

The negative sign of the first term on the right-hand side of Equation 1 corresponds to the reciprocal relation between the object and the speckles described above and $L_0 \tan\theta$ may be regarded as the geometrical multiplication factor. In the second term, $a_z \sin\theta$ is simply the projection of a_z onto the directions of the line sensors. As one can see from a simple geometrical consideration, the effect of a_z on the speckles is in the opposite direction on each of the sensors and hence is added, unlike the effect of a_x being canceled out.

From Equation 1 we get,

$$\varepsilon_x = \frac{-\Delta A_x}{(2L_0 \tan\theta_0)} - \frac{a_z \cos\theta}{L_0} \qquad (2)$$

Then, we can obtain the strain ε_x easily when a_z is negligibly small. Otherwise, we must correct the strain using the value of a_z measured by some means.

The resolution of such strain measurement may be defined as the amount of strain sufficient to shift the speckle pattern on an image sensor by the pitch of its photodiode array. For example, a set of values $A_x = 14$ μm, $L_0 = 560$ mm, $\theta_0 = 45$ deg , $a_z = 0$ yields 1.25×10^{-5} as the resolution through Equation 2.

In actual calculation, A_x is calculated as the position of the peak in the cross-correlation function $C_{12}(j)$ between two linear vectors $S_1(i)$ and $S_2(i)$, where the former represents the frame of intensity distribution on the image sensor before deformation and the latter represents one after deformation. The formula for $C_{12}(j)$ is

$$C_{12}(j) = \sum_{i=1}^{N} \frac{S_1(i)}{\sqrt{\sum S_1^2(i)}} \frac{S_2(i+j)}{\sqrt{\sum S_2^2(i)}} \qquad (3)$$

where N is the number of photosensitive elements in a linear image sensor. It should be noted if $S_1(i) = S_2(i)$ for all i, then $C_{12}(0) = 1$. In other words, if the

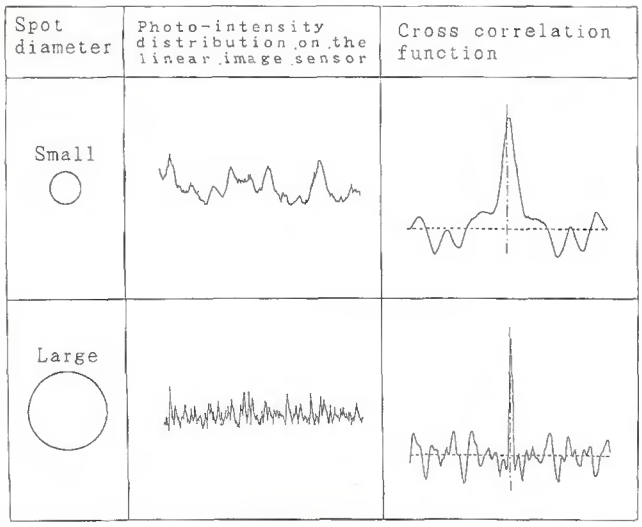

Fig. 3 — Schematic illustrations of relation between the diameter of the laser spot, intensity distribution on the image sensor and cross-correlation function.

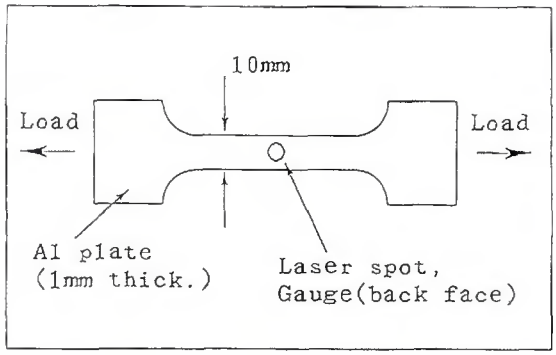

Fig. 4 — Specimen for static tensile test.

speckle pattern does not change at all between measurements, the cross-correlation function will have a maximum with height 1 at j = 0. If the pattern simply shifts without deformation, the maximum peak will shift by the amount of shift in the speckle pattern. Then by detecting the position j_o of the maximum in the correlation function, A_x is given by

$$A_x = j_o\, p \tag{4}$$

where p is the pitch of the sensor elements. From the raw data of $S_1(i)$ and $S_2(i)$, the corresponding mean level was subtracted before calculating $C_{12}(j)$ in order to enhance the visibility of the dominant peak. $C_{12}(j)$ normally needs to be evaluated for only a limited range $-j_{max} > j > j_{max}$, where j_{max} is typically 300, because the position j_o of the peak is expected to be within a certain distance from j = 0 due to the reason below.

Once a series of speckle patterns has been stored into a computer memory, there are options on how to calculate the history of strain out of these frames. The most straightforward approach is to calculate the cross-correlation between each consecutive pair of frames and sum up the strain increment thus calculated. However, this may be troublesome if the strain increment in a single sampling period is not significantly large as compared to the resolution of the system. Therefore, when the rate of strain change is low, it is beneficial to use the first frame as the reference frame and calculate the strain with respect to the reference until the peak of correlation becomes so low that the reference frame needs to be renewed. In any case, j_o is expected to be within a certain distance from j = 0 so that the peak in the correlation function

Table 1 — Experimental Conditions for Dynamic and Static Strain Measurements

Dynamic	Sampling interval	: 0.35 s
	Detection angle (θ_o)	: 45 deg.
	Working distance (L_o)	: 560 mm
Static	Detection angle (θ_o)	: 26 deg.
	Working distance (L_o)	: 770 mm
Ar-ion Laser	Power	: 0.03~0.05 W
	Wavelength	: 514.5 nm
He-Ne Laser	Power	: 0.005 W
	Wavelength	: 632.8nm

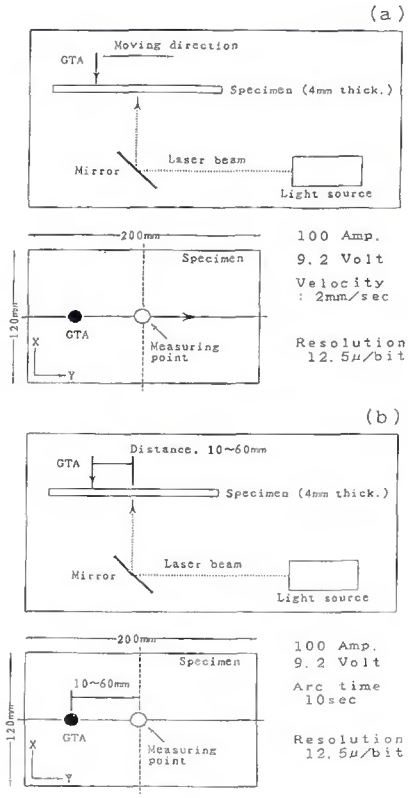

Fig. 5 — Schematic illustrations of measurement dynamic strains. A — With a moving heat source; B — with a stationary heat source.

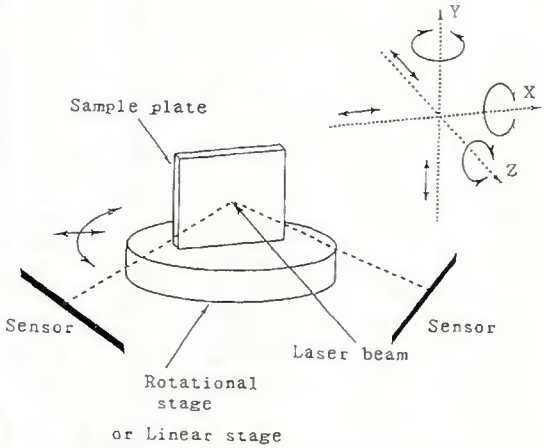

Fig. 6 — Coordinate system in the experiments for rigid body motions.

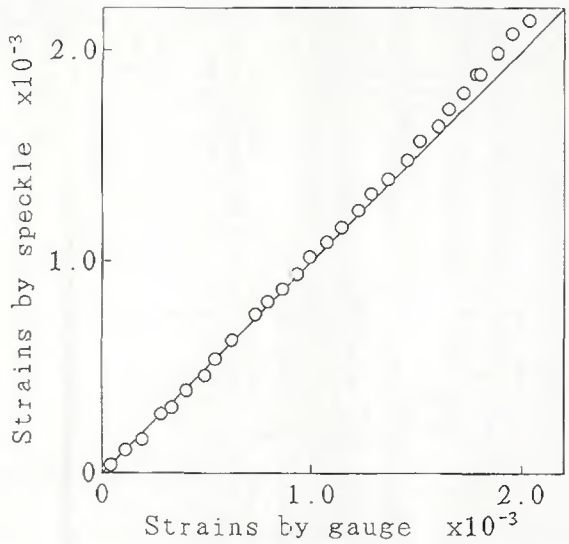

Fig. 7 — Relation between strains obtained by the laser speckle method and those by the strain gauge in the static tensile test.

corresponding to the amount of shift remains distinctive.

Figure 3 shows the schematic illustration of the relation between the spot diameter of the laser beam on the object surface, the speckle pattern, and the cross-correlation function. Since the sensor accepts more information from the spot with a large diameter, the speckle pattern becomes finer. Therefore, precision in determining the amount of shift of the speckle pattern is expected to improve with a larger spot.

Experiments

Static Tensile Test

An aluminum plate of 1 mm thickness as shown in Fig. 4 was used as the specimen for the static tensile test. The specimen was installed on a jig for tensile testing and the laser beam was irradiated to the center of the specimen. Then a tensile load was applied to the specimen in a step-wise manner so that the speckle patterns were recorded at every increment of 5 x 10^{-5} indicated by the strain gauge (1-mm gauge length) mounted behind.

Measurement of Dynamic Strains Caused by a Moving Heat Source

The schematic illustration of the measurement is shown in Fig. 5A. The materials used for measurement are mild steel and stainless steel plates of 4-mm (0.16-in.) thickness. The laser beam was irradiated to the bottom surface of the specimen and a GTA weld was applied to the top surface as a local heat input, as shown in the figure. In this preliminary experiment, strains on the bottom surface were measured to avoid the effects of the arc emission and the shielding gas and to suppress the effect of convection by heat to a minimum. No heat treatment to relieve the stress in the steels was applied.

Measurement of Dynamic Strains Caused by a Stationary Heat Source

This experiment was executed to examine the problem encountered in the measurement for a moving heat source described in the previous section because we can obtain a large number of data with more ease. The experiment was also executed to examine the effects of the spot diameter of the laser beam on the measurement of dynamic strains. The outline is shown in Fig. 5B. The laser beam was irradiated to the bottom surface of the specimen as in the case of a moving heat source and a GTA weld was applied to a specific position on the top surface for 10 s.

Strain gauges were attached to several points more than 20 mm (0.8 in.) away from the heat source for comparison. Strains measured by the gauges were compensated for the temperature change during the measurement, which was always less than 25 K.

Other parameters for the measurements of dynamic strains and the static tensile test are listed in Table 1.

Examination of the Effects of Rigid Body Motion of the Specimen

The rigid body motion of the specimen includes in-plane and out-of-plane movement as shown in Fig. 6, where the coordinate system is defined with respect to the laser beam and the row of the elements in the image sensor. Six kinds of movement must be considered. An aluminum plate was mounted on a rotational stage or a linear stage as shown in the figure, and specific amounts of movement were given to the specimen, and the speckle patterns were sampled every time to examine the effects on the cross-correlation function.

Description of the Laser Speckle System

An Ar-ion laser of 0.03 to 0.05 W was used for the moving heat source experiment. The Ar-ion laser and a 5-mW He-Ne laser were used for the experiment with a stationary heat source. For other experiments only the He-Ne laser was used. Narrow bandpass interference filters were placed in front of the image sensors to prevent the radiation from the GTA weld to reach the sensors. When the GTA weld approaches the measuring point, however, the interference filters cannot cut the emission from the red heated part of the specimen due to the overlap of the wavelength of emission and He-Ne laser. Moreover, the high power of the Ar laser is necessary to compensate for the reduction in the reflectance caused by the formation of oxidized film. A beam expander was used to change the beam diameter, and therefore, the sampling area on the object surface was modified since the statistical properties of speckles such as the mean speckle size strongly depend on the intensity distribution of illumination (Ref. 9). The list of the spot diameter is shown in Table 2.

The image sensor has 2048 elements, but the central 1000 elements were used for analysis. The pitch of the sensor elements is 14 microns and the height is 300

microns. The photo-intensity distribution measured by the image sensor was fed to a personal computer through a digital oscilloscope. Data processing after the experiment was done with a main frame computer. The shortest sampling period of speckle patterns was 0.35 s, limited by the speed of data transfer from the oscilloscope to the personal computer. Moreover, only 31 frames could be accepted during one run of the experiment with this highest sampling rate due to the capacity of the memories available for immediate storage of transferred data in the personal computer. (A frame consists of two patterns fed by the right and left sensors.)

Experimental Results and Discussion

Results of the Static Tensile Test

Figure 7 shows a result of the static tensile test in which the specimen was deformed beyond the elastic limit. The strains obtained by the laser speckle method were compared with those by strain gauges. Even though it is known that a large plastic strain (over a few millistrain for steels — Ref. 10) leads to severe decorrelation of speckles, the good agreement between the two methods here shows that the laser speckle method is applicable even when the material is in the plastic range because we can compare a pair of speckles separated by a small increment of plastic strain even less than 100 microstrain.

Figure 8 shows the comparison of the strains obtained by the laser speckle method with those by the strain gauge within the range of 1 X 10^{-3} strain. Three kinds of spot diameters were used for measurement. Measurement was repeated five times for each spot diameter, renewing the specimen surface using an emery paper after each cycle of loading and unloading. Even though the state of the specimen surface somewhat affects the measuring accuracy in the case of 1-mm spot diameter, correlation between the two measuring methods is fairly good. However, the scatter of the data and errors decrease with increasing the spot diameter. Based on these results, the spot diameter is related to the accuracy of measurement. Effects of spot diameter on measurement will be discussed in more detail later.

Measurement of Dynamic Strains by a Moving Heat Source

Figure 9A and B indicates the change in the peak value of the correlation function and the strain ε_x and ε_y when a GTA weld was made on the stainless steel plates as the moving heat source. Small positive and negative numbers superposed on the lower figures in A and B indicate the vertical scales of strains. The Ar-ion laser was applied directly onto the specimen and the spot diameter was 2.5 mm (0.1 in.). The reference frame was renewed every step because the rate of strain change was relatively high. Similar tendencies were obtained for the mild steel plates. The curves are discontinuous because the measurement was divided into three periods due to the capacity of the personal computer. The correlation values decreased greatly when the heat source was near the measuring point and the strains indicated abnormal values.

The strain behavior before and after the unstable region, however, indicates a qualitatively reasonable tendency. As the arc approaches, the strain increases in tension in the X-direction; whereas, it increases in compression in the Y-direction, and after the unstable region, it shows monotonous contraction due to thermal shrinkage of the plate.

Such an unstable region may be caused by the following factors:

1) The strain rate is so high in this re-

Table 2 — Spot Diameter of Laser Beam for Measurement

	He-Ne	Ar
Dynamic	0.8 mm	1.0 mm
	1.5	2.5
	2.6	3.6
	4.9	7.4
Static	1.0	—
	3.5	—
	5.0	—

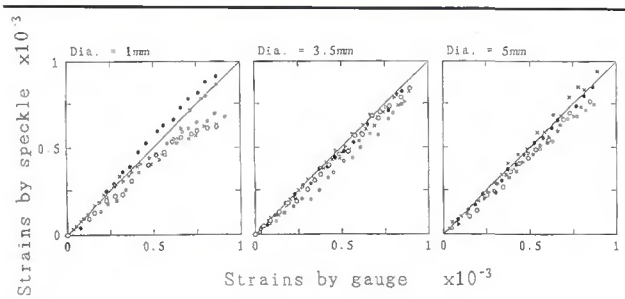

Fig. 8 — Effects of spot diameters on the strain measurement. Strains obtained by the laser speckle method with several spot diameters are compared with the readings of the strain gauge.

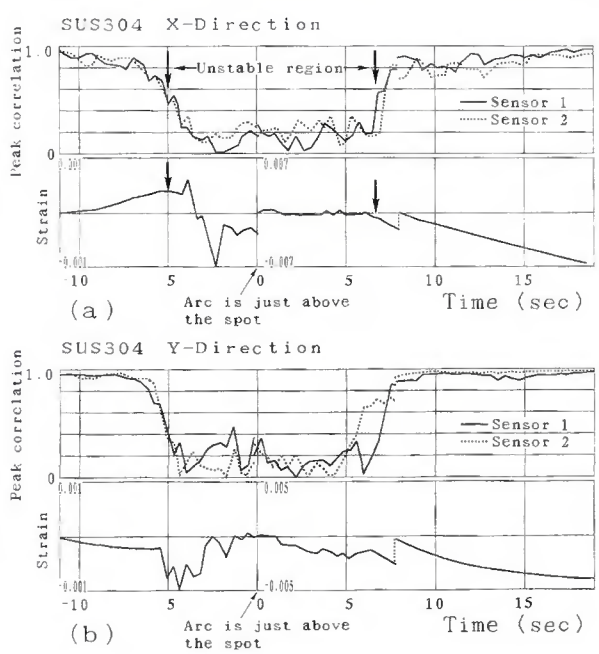

Fig. 9 — Results of strain measurement for a moving GTA weld. Development of peak correlation value and strains are shown. A — X-direction; B — Y-direction.

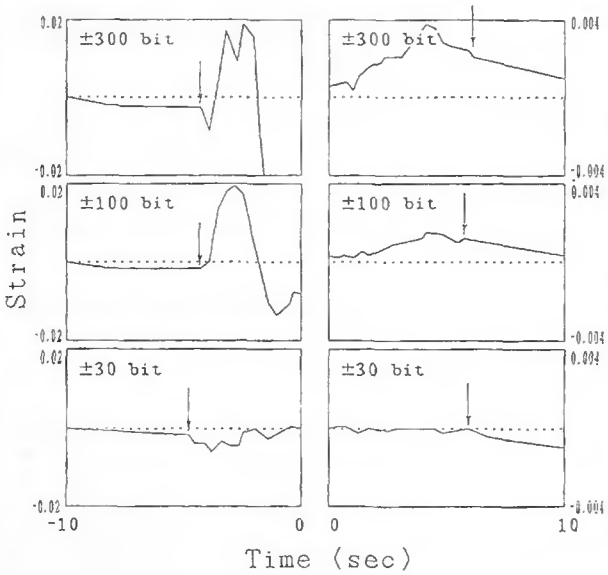

Fig. 10 — Unstable regions for several maximum shift bits in searching position of peak correlation.

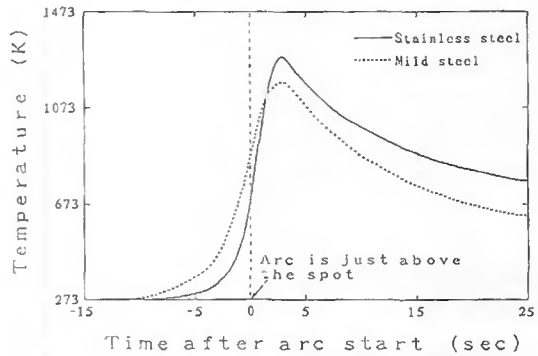

Fig. 11 — Thermal cycles by moving heat sources.

gion that the apparatus cannot follow the change of the speckle patterns with the present sampling rate of 0.35 s/frame.

2) Even if there is a peak in the correlation function corresponding to the amount of shift of the speckle pattern, the computer program automatically picks up the peak with maximum height in the function, which may be different from the desired one because the degree of correlation is very poor in this region.

3) Effects of expansion in the direction of plate thickness at the measuring point of the specimen.

4) Local deflection or movement of the specimen at the measuring position.

5) The strain distribution within the measuring spot becomes nonuniform as the heat source approaches.

6) Rapid surface oxidation or morphology changes at elevated temperatures causing speckle decorrelation unrelated to strain.

We normally calculate the correlation function for the range $-300<j<300$ as described previously. To examine the possibility of factor 2 above, we decreased the value of j_{max} to 30, but there was no remarkable change in the width of the unstable region as indicated by two arrows in Fig. 10. Therefore, we can eliminate 2 as the possibility.

Therefore, factors 1, 3, 4, 5 and 6 remain. With a higher sampling rate, it will become possible to follow the change in the speckle pattern, and the width of unstable region in Fig. 9 would become narrower. If the calculated strain under such conditions does not exhibit any abnormal behavior, factor 1 may be said to be the cause of the unstable region. Before improving our sampling apparatus, however, we felt it necessary to examine the effects of the factors 3, 4, 5 and 6 because they represent a fundamental question that needs to be answered after all.

The peak value of the correlation at the boundary dividing the stable and the unstable region in Fig. 9 was about 0.6 under the condition of the experiments in this section. The temperature of the measuring point at the boundary was 323 to 373 K when the heat source was approaching, and 973 to 1073 K when it was departing. The thermal cycles measured at the point of strain measurement on the stainless and mild steels are shown in Fig. 11.

Model Experiments for the Effects of Rigid Body Motion on the Laser Speckle Method

Factors 3, 4 and 5 in the previous section can be examined by model experiments. The in-plane rigid body motion of the specimen should be canceled by using two image sensors when the motion is in the direction of the row of the sensor elements. With increasing the amount of motion, however, the speckle patterns will change greatly and correlation will fall. Therefore, there must be a limit beyond which canceling becomes impossible.

Moreover, it is impossible to cancel linear motion in the direction perpendicular to the direction of the row of the sensor elements or rotational motion even if it is in-plane motion.

For the out-of-plane motion in Z-direction, correction is possible as described previously. However, the effect of rotation cannot always be canceled.

Therefore, in this section, we examined the effects of rigid body motion on the cross-correlation function and consider its implication in terms of the accuracy of measurement. A sample plate confronting the laser beam is given linear or rotational movement as shown in Fig. 6. The four spot diameters of the He-Ne laser beam on the object surface were adopted as shown in Table 2.

The results were analyzed by using a parameter derived in the following manner. The reference frame was fixed to the first frame and the correlation between each subsequent frame and the reference frame was calculated as the amount of motion increased. Once the peak value of correlation in either right or left sensor became 0.6 or less, the reference frame was replaced by the frame prior to the newest one. The amount of displacement between renewal of the reference frame can be a measure of the rate of decorrelation caused by the motion under consideration.

Effects of Linear Movement

Figure 12 shows the results obtained by the linear movement tests. The amount of displacement between measurements is 0.05 mm. The in-plane movement in the X-direction a_x is in the direction of the line sensors and should be, in principle, canceled by the two sensors. With increasing the amount of movement, however, it became more difficult to cancel it completely because of decorrelation, and at some points it became necessary to refresh the reference frame. The vertical axis indicates this tolerable amount of displacement before a new reference frame is required.

The in-plane movement in the Y-direction a_y is in the direction perpendicular to the line sensors. Therefore, the amount of displacement was remarkably smaller than that in the X-direction. In almost every step, the reference frame had to be renewed for any spot diameters. Therefore, a little displacement in the Y-direction may cause inaccuracy of measurement.

The out-of-plane movement in the Z-direction a_z is equivalent to the expansion in the thickness direction in the dynamic strain measurement, and it is possible to correct its effect if the sensor can follow the change of the speckle pattern. The results clearly show that the speckle pattern is rather insensitive to the movement in the Z-direction movement, and therefore for a given amount of displacement, its effect on measuring accuracy would be less significant as compared to the movement in the X- and Y-directions.

Effects of Rotation

Figure 13 shows the results obtained by the rotation tests. The amount of rotation between measurements is 1.45 x 10^{-4} rad. (0.5′). The vertical axis indicates the tolerable amount of rotation before a new reference frame is taken.

The in-plane rotation Ω_z around the Z-axis makes a nonuniform field of movement in the spot because the amounts of motion differ along the radius. As shown in Fig. 13, the amount of rotation around Z-axis decreases with an increase in the spot diameter because the nonuniformity in the spot becomes stronger with an increase in the spot diameter.

The out-of-plane rotation Ω_y around the Y-axis is in the X-Z plane, which includes the direction of the line sensor and is similar to the linear motion along the X-axis. So the pattern does not come off from the sensor. The amount increased with diameter and the effect on accuracy should be comparatively small.

The out-of-plane rotation Ω_x around the X-axis is in the Y-Z plane, which crosses the direction of the linear sensor, and is somewhat similar to the linear motion along the Y-axis. So the pattern will come off from the sensor for a small amount of rotation, and the degree of decorrelation is severe and will make the strain measurement difficult.

To summarize the effects of the movement of a specimen, it should be realized at first that the direction of the speckle motion with respect to the direction of the line sensor is of primary importance. The accuracy in the laser speckle method can be strongly affected if the movement has a component in the Y direction.

As for the effects of the spot diameter, accuracy is expected to improve with increasing the spot diameter only in the cases of the linear movement in the X-direction and the rotation around Y axis. For the other cases of linear movement and rotation, the benefit provided by a larger spot, *i.e.*, a sharper peak in the correlation function, may be canceled out by a greater degree of decorrelation, *i.e.*, decrease in the peak height.

Effects of the Expansion of a Specimen in the Thickness Direction

The model experiments in the previous section clarified that the displacement in the direction normal to the specimen surface does not affect the degree of correlation significantly. However, we need to examine the expansion of a specimen in the thickness direction caused by the moving heat source in order to correct strain value according to Equation 2, if necessary.

Expansion of a specimen at the measuring point in the thickness direction was measured by using a cantilever-type deflection meter. Figure 14 shows the development of expansion in the thickness direction. By comparing it with Fig. 11, it is obvious that the displacement changes according to the thermal cycles. However, the strain curves corrected by using the results in Fig. 14 showed only a little parallel movement in the stable regions from the original curves. Correction is possible even for the region with rapidly increasing expansion.

Measurement of Dynamic Strains by a Stationary GTA Weld

The results in a previous section indicate that the dependence of correlation value on the spot diameter is specific to each mode of rigid body motion and may provide a clue to what is behind the severe loss of correlation in the experiment with a welding arc. If rigid body motions in the welding experiment were the causes for the decorrelation when a welding arc is near the measuring spot, we could expect a similar relation between the correlation value and the spot diameter as observed in the model experiments. An experiment with a stationary GTA was carried out to examine this point since it is much more efficient to

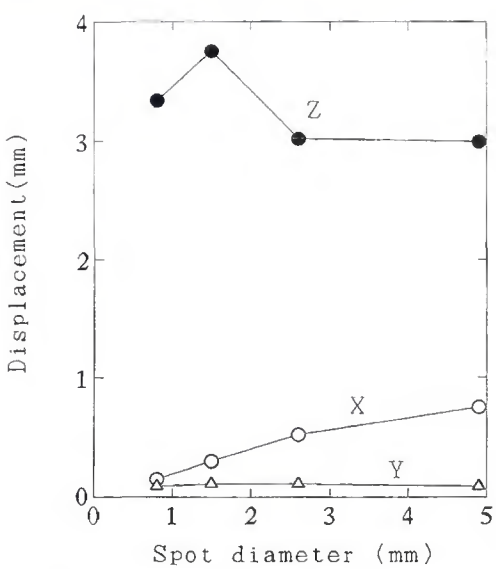

Fig. 12 — Relation between spot diameter and the tolerable amount of displacement before a new reference frame is required.

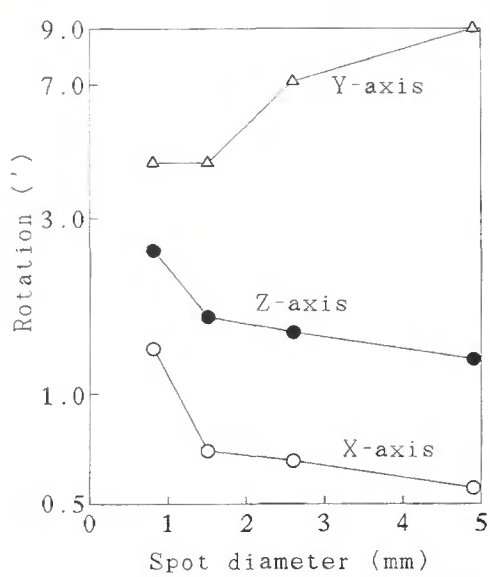

Fig. 13 — Relation between spot diameter and the tolerable amount of rotation before a new reference frame is required.

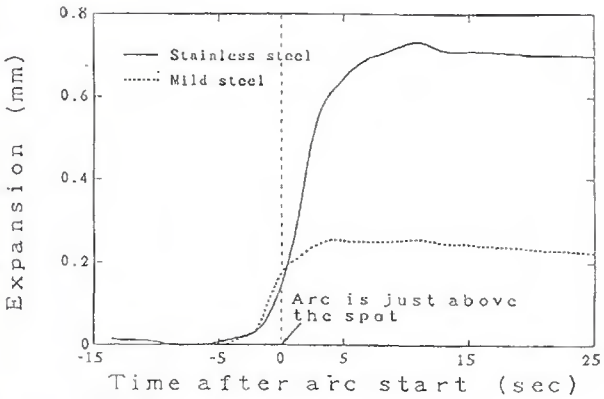

Fig. 14 — Development of expansion in the thickness direction.

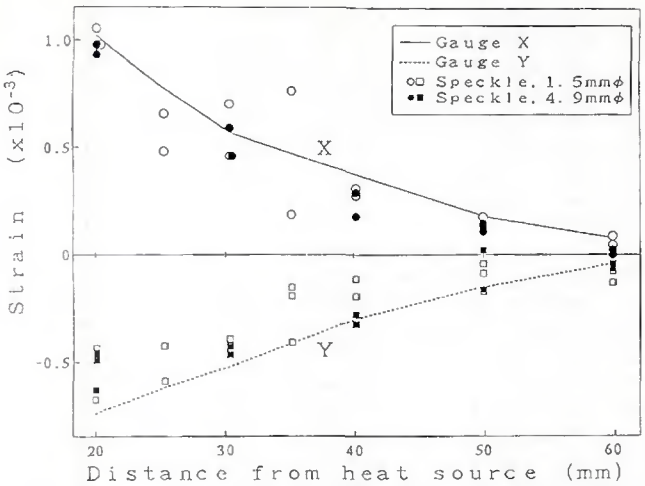

Fig. 15 — Relation between incremental strain change during the period between 3 and 10 s after arc ignition measured by speckle and gauge at various distances from the heat source.

collect data with a different spot diameter, and it is also possible to keep the distance between the arc and the measuring point constant.

Figure 15 shows the comparison between the strains measured by the laser speckle method and strain gauges in the X and Y directions at various distances from the arc for different spot diameters of 1.5 mm (0.6 in.) and 4.9 mm (0.2 in.). The strain in the figure is the amount of strain change from 3 to 10 s after arc ignition. The agreement between the two methods is reasonably good. As may be seen, however, the laser speckle method with 4.9-mm diameter gave slightly better fit with the data by the strain gauges depicted as a solid and a broken curve for the X and Y directions, respectively, and the calculated standard deviation of the speckle data considering the strain gauge data as the true values was 1.47×10^{-4} for 1.5 mm and 1.26×10^{-4} for 4. 9-mm diameter.

Naturally, correlation is high for a small strain and it becomes low when the strain increases for a constant sampling rate. Figure 16 shows the changes of the peak value of the cross-correlation function between two continuous frames of speckle pattern separated by different amounts of absolute values of strain for several spot diameters. As you can see, the general level of correlation with a larger spot diameter is actually lower than with a smaller spot diameter even though the strain value measured with a larger spot diameter seem to be slightly more accurate and precise in this case. Therefore, it should be noted that the peak value of the cross-correlation function cannot be simply used as a measure of precision in the strain measurement when one is comparing results obtained with different spot diameters.

Figure 17 is another view of the results shown in Fig. 16. The amount of strain above which the peak correlation falls below 0.6 is plotted against the spot diameter, and the figure may be compared with the results of the model experiment for rigid body motions such as Figs. 12 and 13. In the hatched region, the correlation value remains higher than 0.6 on the average. The result indicates that the correlation value declines rather steeply with the spot diameter. The modes of rigid body motions, which exhibited this type of negative dependence on the spot diameter, were the linear movement a_y and the rotation Ω_x and Ω_z. As explained earlier, both a_y and Ω_x resulted in a shift of speckle pattern in the direction perpendicular to the line sensors, and therefore there was a severe loss of correlation.

Two data points from the results of the static tensile test are shown in Fig. 17, which seem to exhibit a similar tendency with the results by a stationary GTA weld. It is unlikely that rigid body motion corresponding to Ω_z existed in the static tensile test. Some degree of twist, which corresponds to Ω_x could have been present because a tensile load was applied by means of a screw action, even though mechanical decoupling of the torsion and the axial motion was provided. Another possibility is the strain itself. Since the two different experiments exhibited similar dependence on the amount of strain needed to reduce the correlation down to 0.6 on the spot diameter as shown in Fig. 17 despite very different loading conditions, strain may be the dominating cause of decorrelation in these experiments.

Based on these considerations, the loss of correlation in the experiment with a moving GTA arc seems to be due to one or a combination of the factors, such as a fast rate of strain change and rigid body motions of a_y and Ω_x at the point of measurement.

Conclusion

The laser speckle method was applied to the measurement of dynamic strains in GTA welding; whereby, strains on the bottom surface of a specimen were measured while a GTA weld was applied to the top surface. The results indicate qualitatively reasonable strain behaviors except for the fact that strain measurement becomes impossible when the arc is in the vicinity of the measuring point, due to the severe loss of correlation in the speckle patterns obtained at a constant sampling rate of 0.35 s/frame.

Simple model experiments were carried out to examine the effects of various modes of rigid body motion on the cross-correlation function between the speckle patterns before and after the motion. It was found that the motions, which result in a shift of speckle pattern normal to the row of the sensing elements of the linear image sensors, are highly detrimental.

Then, experiments with a stationary GTA weld were carried out and a comparison was made with the values recorded by strain gauges. By changing the spot diameter of the illuminating laser beam, it was found in both the static tensile test and the experiment with a stationary GTA weld that the accuracy and precision of the strain measurement are better with a larger spot diameter, due to the sharpening of the peak in the correlation functions.

Analysis of those experimental results suggests that the loss of correlation in the welding experiment are probably due to a high rate of strain change and/or detri-

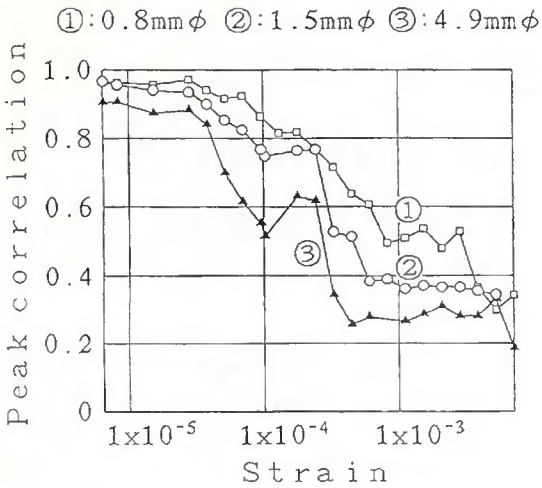

Fig. 16 — Relation between strain increment and peak correlation for several spot diameters.

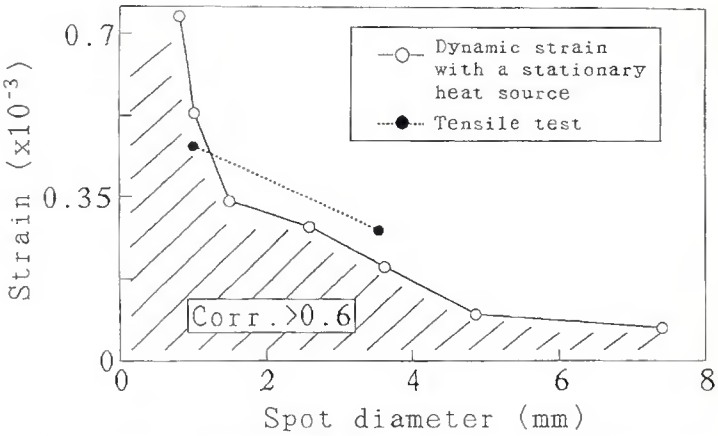

Fig. 17 — Relation between spot diameter and critical strain increment above which the correlation value falls below 0.6.

mental modes of motion at the measuring point caused by thermal distortion. Strong nonuniformity in the strain distribution within the measuring spot, which may exist when the arc is extremely close, may be another contribution to the loss of correlation.

We believe that improvement of the sampling rate will clarify the causes behind the problems in this preliminary study and hopefully lead to more reliable measurement of dynamic strains at high temperature.

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Appendix

Recently, by using a new testing system with maximum sampling rate and capacity of 0.0042 s/frame and 256 frames, respectively, the authors have found that the sampling rate of 0.008 s/frame is sufficient to follow the change of the speckle pattern in the welding experiment reported here. Results will be presented in detail in a future report.