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MEASUREMENT OF HIGH TEMPERATURE STRAIN BY THE
LASER-SPECKLE STRAIN GAUGE

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16. Abstract By using the laser-speckle strain gauge developed earlier and simplified now, the strain of metal at the temperature lower than 250°C is measured in a perfectly   and automatic way. The principle of the gauge is to measure the expansion or contraction of the fine structures of surface by detecting the resultant speckle displacement in an optoelectronic way, whereby the effect of rigid-body motion is automatically canceled out with the aid of a differential detection system. We build a transportable apparatus and performed a comparison experiment with a resistance strain gauge at room temperature. It has a strain sensitivity of 2×10^{-5}, a gauge length smaller than 1 mm, and no upper limit in a range of strain measurement. In the measurement of high-temperature strain it is free from the need for a dummy gauge and insensitive to an electric drift effect. As examples of strain measurement at high-temperature, thermal expansion and contraction of a top of a soldering iron are measured. The interval of the measurement can be made at shortest 1.6 sec. and the change in the strain is clearly followed until the ultimate stationary temperature is reached.

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16. Abstract (cont'd)

   Problems expected for measurement of higher temperature and
   reduction of the measurement interval are also discussed.

MEASUREMENT OF HIGH TEMPERATURE STRAIN BY THE LASER-SPECKLE STRAIN GAUGE **

Ichirou Yamaguchi***

1. Preface

We have developed a method in which the surface strain of an irradiated region is found without any surface contact by automatically measuring the movement of the speckle pattern which occurs when the roughened surface was irradiated photo-electrically with a laser beam [1]. The characteristics of this strain gauge are that: (1) the influence of rigid body motion is eliminated automatically, and the longitudinal strain is directly obtained; (2) the sensitivity of the strain measurement is 10^{-5}, and this is very high for an optical method; (3) since the gauge length is given by the laser beam diameter, it is taken as less than 1 mm. We made this portable type strain gauge for applications to specimens for which it is difficult to use resistance wires. We shall report on the basic principles of this strain gauge, and the results of measuring strain at high temperatures, for which this strain gauge was used.

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2. Basic principles

As a basic principle, this strain gauge has a close relation-
ship with the diffraction grating strain gauge [2 - 5]. This
strain gauge is for discovering a strain by detecting the change
in the direction of diffracted light when diffraction intervals
which were engraved on a mirror surface at regular intervals
receive shrinkage from the surface strain and also by determining
the change in the diffraction grating intervals. There are some
examples of this strain gauge having been used for measuring strain
at a high speed [2 - 4]. Also, although it is not a real time
measurement, the distribution of strain is obtained if the distribution
of the change of the diffraction grating intervals is measured by   /677
the distribution of the directions of diffracted light, by exposing
a laser beam to each point of the negatives on which the image of
a sample surface has been photographed and on which a diffraction
grating is printed [6]. It is considered that a general roughened
surface is a diffraction grating which has irregular ·凹凸
and speckle is equivalent to what is called its diffracted speckle.
Since the diffraction grating intervals are not constant, the space
between the bands is not constant, and it is spatially distributed
continuously and irregularly. Therefore, it is understood that
the speckle moves by a displacement and a deformation of this ir-
regular diffraction grating. Movement of the speckle by a
displacement and a deformation of the surface, and
the deformation which accompanies them is precisely
analyzed by combining the theory of wave optics and the methods of
correlation analysis [7]. The physical meaning of the derived
relationship is simple. Namely, the movement of the speckle is
equivalent to the movement of the diffracted light when a diffraction
grating with certain equivalent intervals undergoes displacement
and deformation. The diffraction grating intervals in this case
are decided by the position of the center of curature of the incident
wave surface and the position of the observation point. On the

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other hand, the speckle deformation occurs because the area of
the roughened surface which is irradiated changes place.
Therefore, not only the strain component but also the rigid body
motion components (translation and rotation) generally overlap.
However, (1) Take the difference of the speckle movement caused
by each beam by irradiating the same point with two symmetrical
beams, or (2) Take the difference of speckle movement at two
symmetrical points by using a single beam [8]. By using either
method, the effect of rigid body motion is automatically cancel-
led out, and only the component of the longitudinal strain is
separated.

3. Optical distribution

Fig. 1 exhibits the layout which was used in this experiment.
The method is to detect speckle movement at two points by using
a single beam. A He-Ne laser is used and, depending on the
reflectance of the samples, a 5 mW laser and an approximately
50 mW laser were properly used. The beam diameter at the samples
which gives the gauge length can be adjusted freely depending on
the lens. For the detection of speckle movement, the speckle is
scanned by a one-dimensional semiconductor image sensor and the
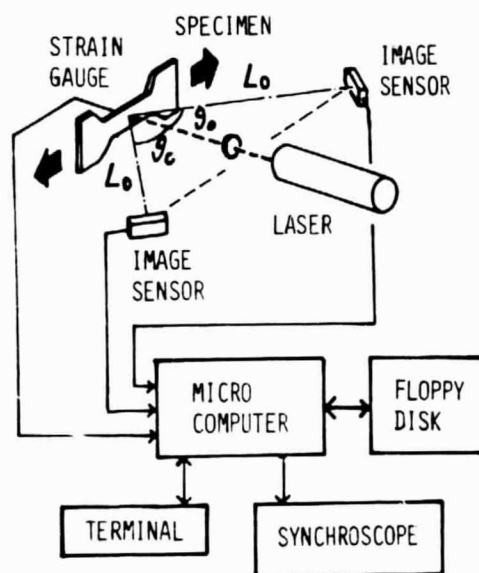output is read on a microcomputer

Fig. 1 Basic display of laser speckle strain gauge   /677

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and speckle movement is calculated as the peak position of the
mutual correlation function between outputs around the area
where strain arises. The laser beam and image sensor are set
up in order to be coplanar. The beam is made to irradiate
almost perpendicularly in order to maintain a uniform beam
strength on both sensor surfaces. However, as is mentioned as
follows, it is not necessary to be accurately perpendicular.

4. The retical relationships of speckle movement

The movement, which occurs in the speckle on the image sensor
from the deformation of the specimen, is given in the following
equations, if the incident beam and the surface made by the
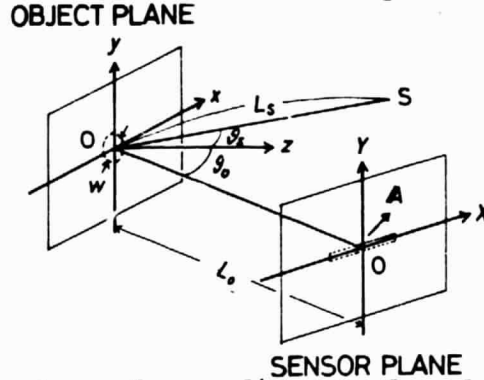sensors are the x-z surface in the system of coordinates in Fig. 2.

OBJECT PLANE

SENSOR PLANE

Fig. 2.   System of coordinates for determining speckle
movement on image sensor.

$$A_x = a_x\left(\frac{L_o\cos^2\vartheta_s}{L_s\cos\vartheta_o} + \cos\vartheta_o\right)$$

$$- a_z\left(\frac{L_o\cos\vartheta_s\sin\vartheta_s}{L_s\cos\vartheta_o} + \sin\vartheta_o\right)$$

$$- L_o\left[\varepsilon_{xx}\left(\frac{\sin\vartheta_s}{\cos\vartheta_o} + \tan\vartheta_o\right)\right. \tag{1}$$

$$\left. - \Omega_y\left(\frac{\cos\vartheta_s}{\cos\vartheta_o} + 1\right)\right]$$

$$A_Y = a_y\left(\frac{L_o}{L_s} + 1\right) - L_o[\varepsilon_{xy}(\sin\vartheta_s + \sin\vartheta_o)$$

$$- \Omega_x(\cos\vartheta_s + \cos\vartheta_o) - \Omega_z(\sin\vartheta_s + \sin\vartheta_o)]$$

where, (a_x, a_y, a_z) describes the translation vector of the

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irradiated area, $(\Omega_x, \Omega_y, \Omega_z)$ the rotation vector, $(\varepsilon_{xx}, \varepsilon_{xy}, \varepsilon_{yy})$ the strain component. Also, ϑ_0 describes the angle of incidence of the beam, L_S the radius of curvature of the wave surface of the beam on the material surface, ϑ_0, L_0 is the angle made by the surface normal line and the sensor, and the distance between the irradiation point and the sensor.

If the difference between the speckle movements which are detected by the two sensors in Fig. 1 is taken, most of the terms in equation (1) are eliminated, and

$$\Delta A_x = A_x(\vartheta_0) - A_x(-\vartheta_0) = -2L_0\varepsilon_{xx}\tan\vartheta_0$$
$$-2a_z\sin\vartheta_0 \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots \quad (2)$$

Namely, only the longitudinal strain ε_{xx}, which is parallel to the surface made by the sensor and the incident beam and the term parallel to the translation a_z, which is perpendicular to the material surface, remain. Also, it does not depend on the angle of incidence ϑ_0, or on L_S, which is determined by the lens power and the position in which it is inserted between the laser and the materials. Therefore, when a_z is sufficiently small, the strain value is obtained by using the following equation from ΔA_x which is observed.

$$\varepsilon_{xx} = -A_x/2L_0\tan\vartheta_0 \quad \cdots\cdots\cdots\cdots\cdots\cdots \quad (3)$$

However, for the correlation peak of the output of the one dimensional sensors to appear clearly when the deformation given to the material is detected, the speckle motion component A_y which is perpendicular to the sensor must be sufficiently small. More accurately, it is necessary that A_y be smaller than the total of the mean diameter $\lambda L_0/w$ (λ : laser wave length: w beam diameter) of the speckle on the sensor and the width of the sensor.

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In the method which uses two symmetrical beams and a sensor, the difference of speckle movement does not receive the influence of η and is proportional to only ε_{xx}. However, the arrangement becomes more complex, as a system which alternately irradiates the beams, etc., becomes necessary [1].

5. Detection of speckle movement

The image sensor which was used for this experiment was a RETICON RL 1728 H which is an MOS type photodiode array, and pitch was 15 μm, width was 14 μm, and number of elements was 1728. It is not necessary to use all of the output of the 1728 elements for the calculation of correlation, and a sufficiently clear correlation peak was obtained from around 512 elements. According to this, the correlation calculation time is greatly shortened. The output signal of the sensor is input to a microcomputer (LSI-11/2, 64 KB) by an A/D converter with clock 25 KH$_z$, 12 bit (DATEL-STLSI-2 is used). The correlation calculation was performed after this signal was made binary depending on whether or not it was above the mean level or below the mean level, and shortening the calculation time was performed.

6. Comparison experiment with a resistance wire strain gauge

The relationship mentioned above was experimentally confirmed by putting a 5 mW laser with 0.9 mm $1/e^2$ diameter in the middle part of a brass specimen which has the standard configuration shown in Fig. 1 (length 100 mm, width of the neck 20 mm, thickness 1 mm) and applying a tension in the x direction. Surface treatments such as rough shear or painting, etc. were not performed on this specimen. A resistance wire strain gauge of 2 mm gauge length was put on the right backside of the beam spot, and the output was also entered in the microcomputer. Fig. 3 exhibits the output wave shapes (a) of both sensors before tension, (b) the output wave shapes after tension, and the mutual correlation function (c) between the wave shapes of each sensor.
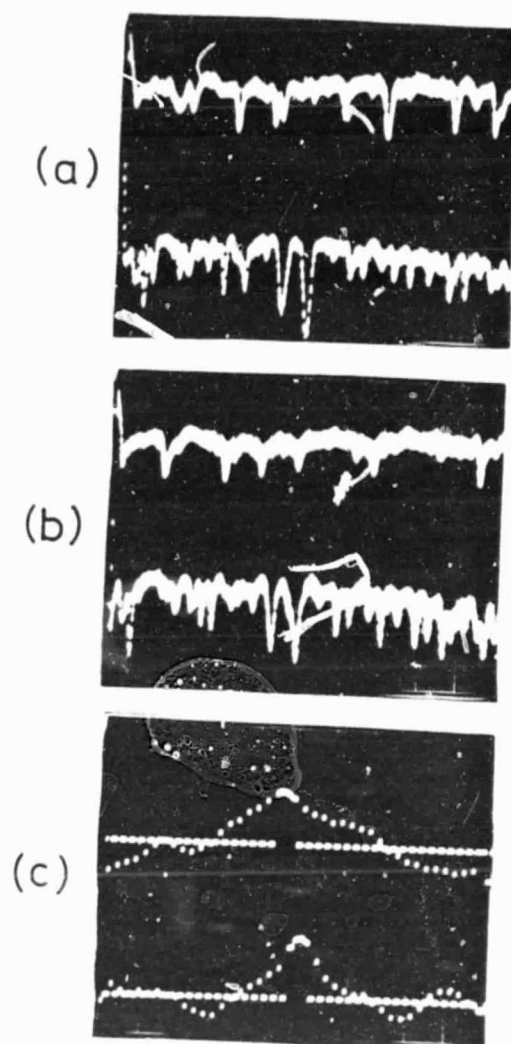
Fig. 3. Output wave shapes of each image sensor (before loading (a) after loading;(b) and mutual correlation function; (c) of wave shapes before and after loading).

The change of the strain by a resistance wire strain gauge in this case is 200 microstrain and the area of the correlation peak is proportional to it. In order to quickly perform the detection of the correlation peak position; first of all, the correlation function toward the shifting slide which was thinned is calculated

and the maximum position is found among them. Next, only the
region around the maximum position is calculated using small inter-
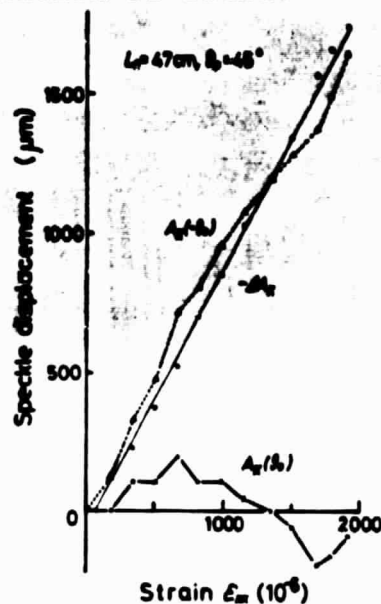vals and the final peak position is found.

Fig. 4. The reading of the resistance wire strain gauge
and speckle movement on each image sensor and the
difference between them.

Figure 4 exhibits the values of the speckle movement obtained
by stretching a portion of the specimen in 100 μm steps and
adding up compared to the reading of the resistance wire
strain gauge. The speckle movement on each sensor shows a complex
action as the strain and the effects of rigid body motion differ
depending on the position of each sensor. However, it is under-
stood that the difference between is sufficient on the
slope of the straight line which was calculatee in Equation (3).
However, it is considered that the reason why the straight line
does not go through the origin is that the output of plane transla-
tion a_3 shown in Equation (2) is large at the initial time when
the load is applied.   /679

7. Strain measurement at high temperatures

It became clear from the above experiment that this method
functions as a noncontact strain gauge. The amount which is
measured by this strain gauge is longitudinal strain itself which

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is defined geometrically as is shown in the theoretical analysis. Therefore, we considered an experiment using this method in the field, where it is difficult to use a resistance wire strain gauge. First of all, the strain from heated and cooled metals was chosen as an immediate subject, and as a subject in which the strain change is rather slow. Even if the specimen is at a high temperature, the strain as a total of thermal strain and mechanical strain can be measured by this strain gauge if the effects on the speckle movement of convection, etc. of the air can be ignored. The measurement time of this strain gauge is constrained by the correlation calculation time according to the method in which speckle movement is found every time as the above mentioned static strain measurement. For example, if the number of correlated points is 40, the measurement time is about 10 seconds.

In the case when deformation occurs continuously, such as the strain with a temperature change, the best way is that the output signal of the image sensor is read continuously into auxiliary memory, and the correlation function between the approximate data is calculated after summarizing them later. We took the method of writing the data, which was A/D converted to the floppy disk which belongs to the microcomputer. The sample intervals in this case are mainly determined by the writing speed of the disk. In the case when 750 elements of each sensor output are entered, the writing speed of the disk was about 4.3 sec.

As a subject, the strain from heating and cooling of the tip of a cylindrical surface of a 20W soldering iron was measured. Fig. 5 exhibits a picture of the equipment. The data for 80 repetitions can be written on a disk (capacity 1 MB). A thermocouple was installed at a position of about 1 mm from the edge of the irradiation spot, and the temperature was also entered into the computer at the same time. Since the reflectance of the surface of a soldering iron is low, an output of approximately 50 mW was used for the laser and, by using a lens of 300 mm focal length, a spot of about 2 mm diameter was focused on the measurement
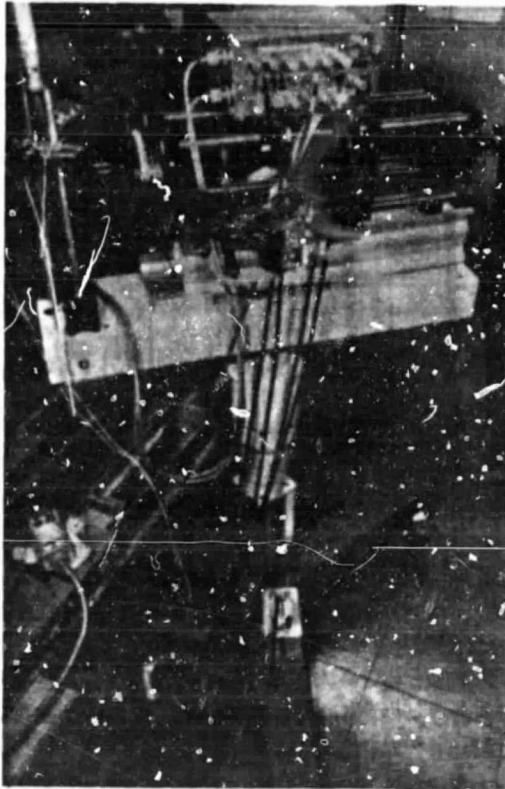
Fig. 5.   The measurement position of the high temperature strain of a soldering iron.
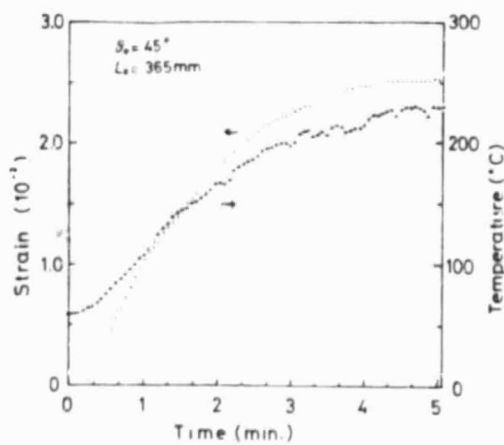

Fig. 6.   Results of measurements of the temperature change of the tip of the soldering iron and the strain toward the axis of the soldering iron.
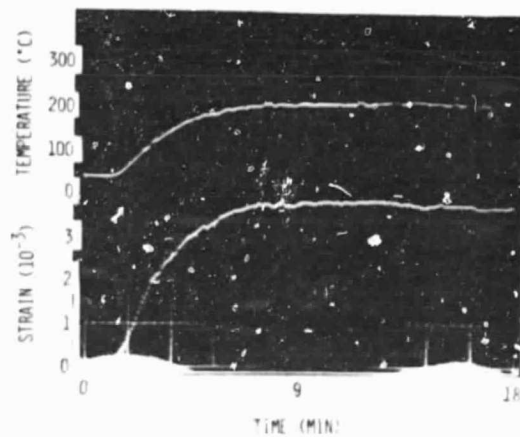
Fig. 7.   Temperature of the tip of the soldering iron when it is heated and which is displayed on synchroscope, and the measurement results of the time change of strain toward the axis.

point. As is shown in Figure 5, the laser light source was
not included in the strain gauge and the gauge was put on a
portable type laboratory table with wheels. Since it was deter-
mined that light does not enter the image sensor except from the
spot position, measurements can be performed in a bright room.
Eight seconds after the soldering iron was turned on, the output
of both sensors was input every 4.3 seconds.

Figure 6 exhibits the strain measurement results with
respect to the axis of the soldering iron.   In this case the
value of the strain was directly calculated by Equation (3). No
strain was found 20 seconds before the soldering iron was turned
on; as temperature change was fast, the strain change was too large,
and the clear correlation peak shown in Figure 3 (c) was not
obtained. After this point was passed, the change of the strain
became mild, and always a clear correlation peak began to occur.
The temperature was found by inputting in a microcomputer after
the terminal voltage of a copper constantan thermocouple   /680
maintained at zero degrees with ice water was amplified by direct
current in order for the maximum value to become below 5V, and
12 bit A/D conversion was performed. It is considered that the
reason why the temperature varies is that the contact condition of
the thermocouple was incomplete. However, the value of strain
always changed smoothly and it almost followed the mean temperature
change. In this case the minimum strain change which it is possible
to detect is that the difference of speckle movement is equivalent
to the case which is equal to pitch 15 µm of the image sensor, and
this is ΔA_x microstrain in the current arrangement. On the other
hand, the upper bound of the measurement range can be extended as
much as we can by adding small changes as the above. However, in
the case when the irradiation point begins drifting, it is necessary
to adjust it by the proper method. According to the above method,
the number of measurement points is constrained by the writing
capacity of the floppy disk. As one of the methods of eliminating
constraints, shortening the calculation time of the correlation

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function has been considered. For phenomena such as strain by the temperature change, if sample intervals become short, speckle movement becomes small and the calculated point of correlation can be generally decreased. Therefore, a method was used in which 512 element of image sensor output is input to microcomputer and the peak was found by calculating the correlation with previous output with 12 points. In this case the intervals for samples were 5.2 sec. The temperature and the strain value in each step were written in the interval memory of the microcomputer and those time changes can be displayed on a synchroscope or record meter at the time when all the measurements have been finished. Figure 7 exhibits that the temperature and the strain measurement results toward the axis are displayed on the synchroscope, and the arm of the image sensor of the strain gauge was obtained parallel to the axis of the soldering iron. The soldering iron was turned on one minute after the beginning of the measurement, and it is perfectly understood that the soldering iron began expanding from that point.

Figure 8 exhibits the relationship between temperature and strain. The figure clearly shows the proportional relationship between temperature change and strain. The applied slope of the straight line is 22.9×10^{-6}°. On the contrary, Fig. 9 exhibits the progress of strain after power was cut. The time when current was cut is also after one minute. The change of strain in this case is very smooth. Figure 10 exhibits the relationship between temperature and strain in this case.

Compared to Figure 8 the deviation from the straight line at high temperature and low temperature is conscpicuous. Also, the slope of the straight line becomes 17.2×10^{-6}° and this is very different from the case of heating.

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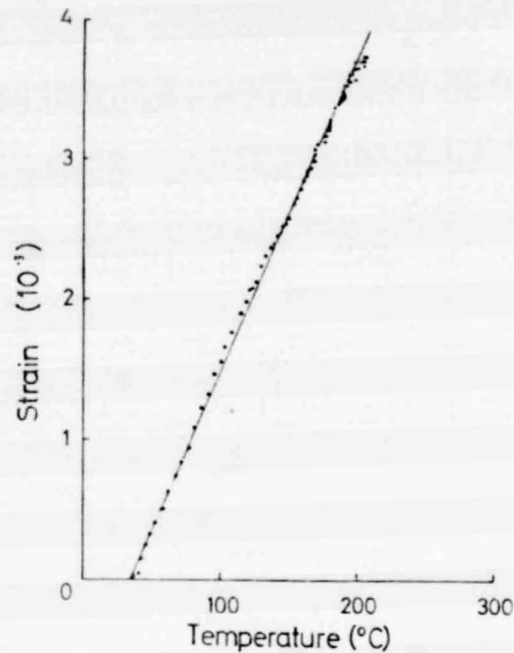
/680

Fig. 8. The relationship between temperature and strain
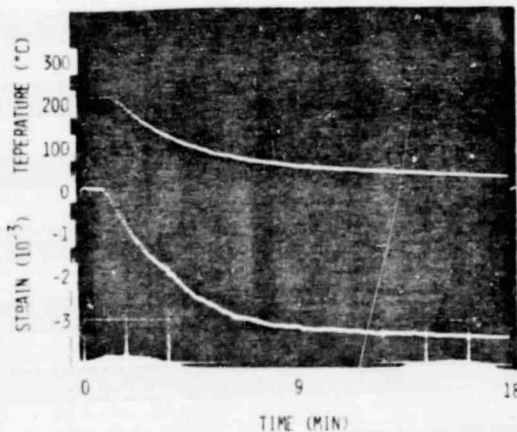toward the measurement results of Figure 7.

Fig. 9. The temperature during
cooling of the tip of the solder-
ing iron displayed on synchroscope
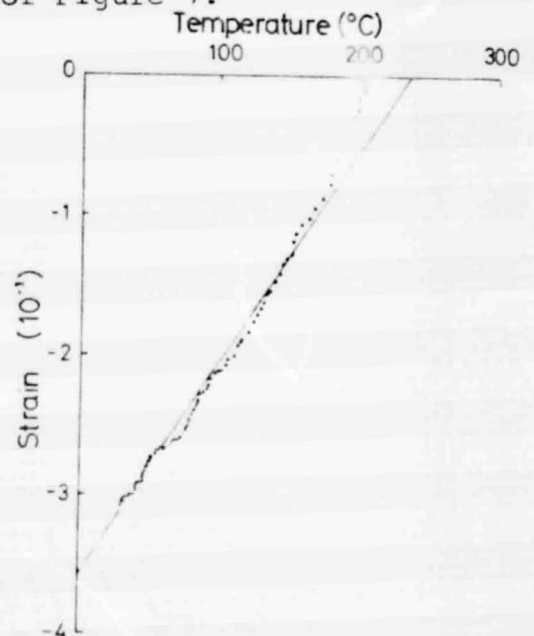and the results of measuring the
time change of strain toward axis.

Fig. 10. The relationship
between temperature and
strain toward the measurement
results of Figure 9.

The following can be assumed from the above result. According to the Science Chronological Tables, the coefficient of linear expansion of copper for the material of the soldering iron is 16.7×10^{-6}°. Therefore, in the case of heating, it is considered that $(22.9 - 16.7) \times 10^{-6} = 6.2 \times 10^{-6}$/deg is the mechanical strain from the thermal stress per 1°C. On the other hand, the mechanical strain in the case of cooling becomes $(17.2 - 16.7) \times 10^{-6} = 0.5 \times 10^{-6}$/deg. It shows that cooling is uniformly performed, and since the temperature gradient is small, almost no thermal strain by free contraction occurs. The circumferential strain can be measured if the arm of the image sensor is transversed to the arm of the soldering iron. Figure 11 exhibits one of the examples of the results of the heating.

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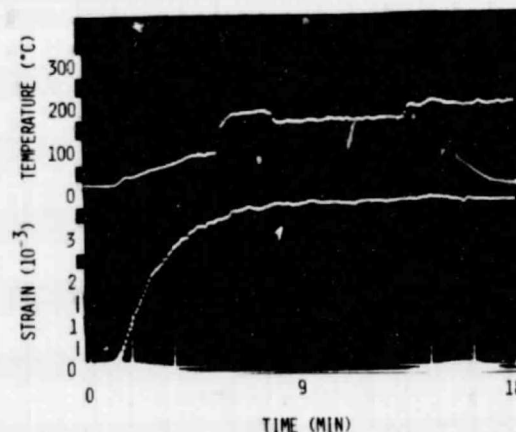

Figure 11. The temperature at heating of the tip of the soldering iron displayed on the synchroscope and the measurement result of the time change of circumferential strain.

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A remarkable discontinuity which is considered to have occurred because of imperfect contact of the thermocouple is seen, but strain changes almost continuously. In our measurement result there is generally discontinuity in the strain change at the time of heating although the discontinuity is very small. On the other hand, almost no discontinutiy was seen at the time of cooling. Therefore, it can be assumed that the cause of the discontinuity is not from oscillation of the strain gauge, etc. It is considered that correlation was probably insufficient and speckle movement on image sensor exceeded the 12 point correlation.

8. Examination

It has been reported that the examples of strain measurement at a high temperature by optical methods are ones for which the speckle interference method was used [9], the applications of the Moire method [10] and furthermore, the method for which digital image processing is used together with the Moire method [11], etc. In these methods, a two-dimensional distribution is obtained; on the other hand, it is difficult to find directly a strain value in real time, and strain sensitivity is about 10^{-4} at the highest. Printing a diffraction grating on the surface is necessary for the Moire method. It is not necessary to process the surface for the speckle interference method, but since the obtained diffraction pattern is the contour of the in-plane displacement, it must be differentiated. This method, which is basically a measurement of strain at every point, has the following characteristics. It is possible to find strain directly in a short time without any surface contact and the gauge length can be taken as less than 1 mm, with a strain sensitivity of approximately 10^{-5}. The measurement temperature this time was less than approximately 250°C; but an experiment for higher temperatures has also been prepared. The problem of most concern in this case is the effect on the speckle movement of air convection.   /682

If the gradient of the refractive index of the air changes, the speckle moves and, during the measurement, steps must be taken to control the changes in temperature gradient. For this, methods

of putting a specimen and an image sensor in an exhaust cell and removing the intervening air were considered. Also, in the case when the temperature becomes high and the specimen radiates if an interference filter is used for which wavelength is suitable for the laser light, speckle can only be set up with an image sensor by controlling the radiated component. Because of that, this method can be applied.

The surface for which this method can be used could be anything if it can diffusely reflect light. However, the case when the above speckle relationship is formed is when the fine structure of the measurement surface is sufficiently fine compared to the laser beam diameter. Even if a mirror reflection component occurs, such as from a smooth metallic surface, there is no problem since the speckle in the position where the mirror reflected light does not reach has a high contrast, and it moves according to the above rule. The samples which have been successfully measured so far are metals, rubber, paper, plastic and painted surfaces under ordinary temperature. However, it might be necessary for many samples to use a strong Ar laser, etc. rather than the He-Ne laser which was used in this experiment as the surfaces oxidize and the reflection rate decreases at high temperature. However, it is not necessary to also change the optical arrangement for that case, as the movement of speckle does not depend on the wavelength.

The minimum sampling interval in this experiment is about 1.65 seconds, by using a method of writing the outputs of image sensors in order on a floppy disk. In order to shorten the intervals easily, for examples, the output waveform of the image sensor is continuously stored in an analog data recorder. And later on, if the method of calculating speckle movement by reading the output waveforms gradually is taken, sample intervals can be moved to the 40 msec scan cycle of the image sensor. Furthermore, instead of calculating correlation by microcomputer the detection of speckle movement was made high speed by using an IC chip for calculation of the correlation, and calculating the repetitions of output of

a spatial filter photodector [12]. In the case when the spatial filter photodetector is used, it is necessary to decide the sign of speckle movement. The possibility of detecting the sign is being studied currently by performing a simulation experiment of the spatial filter detector by using image sensor and microcomputer.

Since shearing strain ϵ_{xy} is effectively the same as in-plane rotation ω_z, is not suitable for the measurement of shearing strain. (Refer to Equation (1)). Therefore, it becomes necessary for the general measurement of strain to put out arms of the image sensor in three directions like a rosette gauge, and the equipment becomes quite large scale. However, it might be possible to implement a rosette type system if the equipment can be made much smaller by using a semiconductor laser and fiberoptics which have been making rapid progress.

9. Conclusion

Strain below 250°C could be completely measured automatically by simplifying laser speckle which was previously developed, and by applying it to strain measurement at high temperature. Gauge length was 2 mm, strain sensitivity was about 2×10^{-5}. This strain gauge is for detecting the shrinkage of surface fine structure with light and for measuring itself, and a dummy gauge is not at all necessary. The shortest measurement time is 1.6 seconds with the current equipment. It is considered that this strain gauge can definitely be used up to 300°C. Problems which are considered for the measurement at higher temperature and also shortening the measurement time were also studied.

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