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Demonstration of Laser Speckle System on Burner Liner Cyclic Rig

by

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for

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16. Abstract
A demonstration test was conducted to apply speckle photogrammetry to the measurement of strains on a sample of combustor liner material in a cyclic fatigue rig. A system for recording specklegrams was assembled and shipped to NASA Lewis Research Center, where it was set up and operated during rig tests. Data, in the form of recorded specklegrams was sent back to UTRC for processing to extract strains. Difficulties were found in the form of warping and bowing of the sample during the tests which degraded the data. Steps were taken by NASA personnel to correct this problem and further tests were run. Final data processing indicated erratic patterns of strain on the burner liner sample.

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1.0 INTRODUCTION

1.1 Background

One of the recognized techniques for measuring the strain on a surface involves measuring changes in the speckle patterns obtained from photographs of the surface under laser illumination. The photographs are recorded before and after thermal or mechanical deformation of the surface and they capture the surface distortion as a corresponding distortion of the laser speckle pattern. The photographs are subsequently compared on an interferometric photocomparator to measure differential magnification, which corresponds to strain. A laser speckle photogrammetry system has been developed at United Technologies Research Center based upon this technique, partly under the sponsorship of the National Aeronautics and Space Administration through contracts NAS3-22126 and NAS3-23690. The first of these contracts, NAS3-22126, was a study of methods for measuring static strain on burner liners at temperatures up to 870°C. Under this contract, the laser speckle photogrammetry system was shown to be capable of measuring the thermal expansion of a hastelloy X sample at temperatures up to 870°C under laboratory conditions. Under the second contract, NAS3-23690, the laser speckle photogrammetry system was applied to the measurement of strain on a burner liner operating in a high pressure, high temperature, burner test facility.

One of the problems in the use of this technique is optical distortion caused by turbulent high pressure gas within the viewing path. Although the effects of this problem may be analyzed if the distortion is precisely known, the turbulence encountered around an operating burner is random and not well documented. One of the objectives of the experimental work in contract NAS3-23690 was to evaluate this problem. The results indicated that, in its present state of development, speckle photogrammetry can only be used at pressures below approximately three (3) atmospheres. At higher pressures, turbulence of the gas within the viewing path causes the speckle pattens to blur and fail to correlate between photographs.

1.2 Objective

The objective of this contract was to demonstrate the use of the UTRC Speckle Photogrammetry System on the Burner Liner Cyclic Fatigue Rig at NASA Lewis Research Center. This rig is used to subject samples of burner liner material to cyclic stresses in order to study phenomena such as thermomechanical deformation and fatigue. Temperature distributions on the samples were measured accurately with thermocouples and an infrared thermal scanner.

Electrical static strain gages cannot operate in excess of 650°C. Laser Speckle Photogrammetry offered a means for measuring static strain distributions at very high temperatures and thereby increasing the utility of the Burner Liner Cyclic Rig. Since the rig operates at ambient pressure, distortion due to turbulent gas was not expected to be a problem. The contract involved the temporary use of the UTRC specklegram recording system at the NASA Lewis Research Center to record specklegrams that were subsequently processed for strain data at UTRC utilizing the automated interferometric comparator.

1.3 Program Tasks and Management

The program consisted of five tasks listed as follows:

- Task 1: Preparation, Delivery, and Checkout of the Specklegram Recording System
- Task 2: Operation of the Specklegram Recording System During Testing with the Burner Liner Cyclic Rig at LeRC
- Task 3: Data Reduction from the Recorded Specklegrams
- Task 4: Review of Results
- Task 5: Preparation of Reports

1.4 Summary of Results

The speckle photogrammetry system was successfully transported to NASA LeRC and operated there by both UTRC and NASA personnel. In a total of three data runs, 72 specklegrams were recorded and examined. The first set of 24 specklegrams exhibited lack of correlation, and this was traced to out-of-plane warping and tilting of the sample in the burner rig. Steps were taken to reduce this problem; however, both the second and third runs also exhibited correlation problems although to a lesser degree. Data was extracted from correlating areas on those pairs of specklegrams that could be processed. This data shows erratic patterns of strain on the sample.

2.0 PREPARATION, DELIVERY, AND CHECKOUT OF SPECKLEGRAM RECORDING SYSTEM (TASK 1)

2.1 Procurement

2.1.1. Fused Quartz Window for the NASA Rig - The contract specified that an optical quality window, compatible with requirements of laser speckle photogrammetry be procurred for use in the NASA Burner Liner Cyclic Rig. This window was ordered and delivered to NASA LeRC.

2.1.2 Procurement of Photographic Plates - Three boxes (20 plates each) of AGFA 10E75 photographic plates were ordered for use on this contract.

2.1.3 Spare Laser Mirror - A spare mirror was purchased to replace one of the laser mirrors in the event that it failed during operation.

2.2 Fabrication (Hardware and Software)

2.2.1 Holder for Plate Labeling Optics - A holder for the optics associated with printing labels onto the specklegram plates was fabricated. This unit mounted directly on the optics pallet and supported the LED display, the relay lens, and a mirror to direct the image onto the side of the specklegram.

2.2.2. Laser Control Electronics - Software and hardware modifications were required to modify the control electronics previously used with the Q-switched JK laser so that it would function with the open cavity Korad Laser. These modifications were determined and were implemented. The operating program was also modified to print the time of day on the plate so as to insure identification of the operating conditions under which each photograph was recorded.

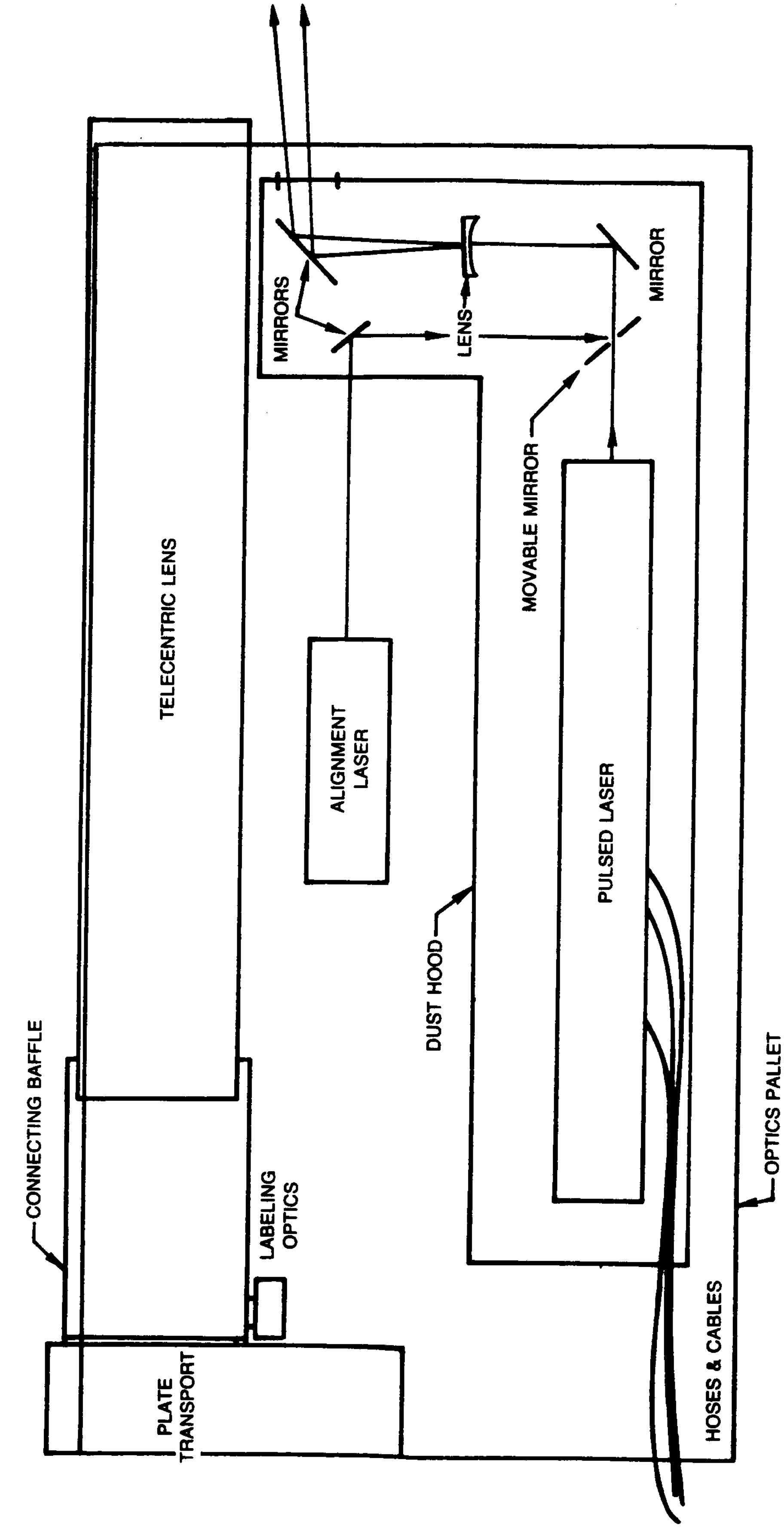
2.2.3. Lens Baffle - A baffle housing was designed to make a light tight connection between the telecentric lens and the plate transport with provision for the plate labeling optics.

2.2.4 Optics Layout - A layout of components on the optics pallet was completed and is shown in Fig. 1.

2.2.5 Cables - Cables were prepared for the 150 foot run from the burner rig to the control room. These included the computer interconnection, the laser charge and dump controls, the plate change indicator, and the sequence initiation control.

FIG. 1

OPTICAL SYSTEM LAYOUT



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2.3 Preparations

2.3.1. Rotation of the Burner Rig - Information obtained from Air Force contract F33615-83-C-2330 indicated that mirrors employed in the optical system for laser speckle photography could create large erroneous apparent strains. This information was communicated to NASA with the suggestion of rotating the Burner Liner Cyclic Rig by 90° about its axis to eliminate the use of a mirror. This decision was essential to the final layout of the optical components of the Laser Speckle System.

2.3.2 Laser Checkout - The Korad laser was checked out and found to require several repairs. This included replacement of the flash lamp and its connectors, cleaning the laser mirrors, and desensitizing the fire circuit to allow for long cables to be attached. Laser operation was quite reliable after this work was performed.

2.3.3 System Checkout - The entire system was checked out by recording a photograph of a piece of heat blackened Hastelloy X. All facets of the system operated properly and the exposure of the photographic plate was ample.

2.4 Shipping

2.4.1 Shipping Specklegram Recording System to NASA LeRC - The specklegram recording system and the Korad pulsed laser were packed and shipped to NASA Lewis Research Center. The equipment was delivered on schedule and in excellent condition.

3.0 OPERATION OF THE SPECKLEGRAM RECORDING SYSTEM DURING TESTING WITH THE BURNER LINER CYCLIC RIG AT LeRC (TASK 2)

3.1 Setup and Data Run at NASA LeRC

Two UTRC personnel traveled to NASA Lewis Research Center and arrived on the day of delivery of the equipment. The equipment was unpacked and set up during the first day. This included aligning the height, lateral and longitudinal position of the specklegram recording system. The laser was connected to its cooling unit and power supply and checked out. The cables were routed to the control room and hooked up to the recording system. The second day was spent in a final check-out the system and performing a data run. Specklegrams were recorded at ambient temperature and at increments of approximately 100°C up to 900°C and back down to 120°C. Following this, three pairs of specklegrams were recorded while cycling between the extreme temperatures, and this was followed by a final recording at ambient temperature. The plates from the data run were developed at NASA LeRC. The third day was spent familiarizing NASA personnel with the operation of the system. At the end of third day UTRC personnel returned to UTRC with the specklegram recordings.

3.2 Rig Testing and Modifications

Based upon information from UTRC data evaluation of the first run, tests were performed by NASA personnel to check for tilting of the sample. A small spot in the center of the sample was illuminated by a CW laser and a TV camera, focused at infinity, was located at the image of this spot. The aperture at the center of the lens was imaged on the camera sensor and appeared on the TV monitor. Speckles were observed within the telecentric lens aperture and they were seen to move horizontally as the sample was heated. A video recording was made of this speckle pattern for a sequence of heating and cooling of the sample, and this recording was sent to UTRC for evaluation. Between maximum and minimum temperatures, speckles were noted to move about four aperture diameters. This indicated excessive tilting about a vertical axis in the order of 6° due to heating of the sample. Steps were taken by NASA personnel to mount the sample more securely. Two additional data runs were performed by NASA personnel, one at the same temperatures as the first data run and the second with reduced temperature increments.

4.0 DATA REDUCTION FROM THE RECORDED SPECKLEGRAMS (TASK 3)

4.1 First Data Run Evaluation

Figure 2 shows a print from one of the speckle photographs with the thermocouples and their lead wires clearly visible. The run number, plate number, and time of day, which were printed on the plates, appear backwards in the upper left corner of the figure due to the inversion necessary to correct the image. The thermocouple temperatures which were monitored and recorded at each specklegram exposure are as follows:

Plate	Temp°C	Time	Plate	Temp°C	Time
1	13°C	12:57:16	13	495°C	14:10:57
2	121°C	13:18:17	14	365°C	14:15:15
3	167°C	13:25:22	15	168°C	14:20:16
4	387°C	13:30:24	16	123°C	14:23:41
5	511°C	13:34:36	17	888°C	14:29:21
6	618°C	13:38:55	18	127°C	14:35:42
7	711°C	13:42:18	19	888°C	14:40:44
8	807°C	13:47:00	20	126°C	14:44:17
9	896°C	13:50:40	21	886°C	14:52:16
10	894°C	13:56:39	22	126°C	14:59:46
11	802°C	13:59:39	23	12°C	15:13:02
12	711°C + 618°C (double-exposed)				

Specklegram number 12 was an accidental double exposure which resulted from a failure to advance the plate after the recording was made. An addition was made to the operating program to sound a warning signal after each exposure to alert the operator and avoid a recurrence of this error.

Pairs of specklegrams were compared on the heterodyne photogrammetric comparator and it was found that most pairs exhibited very poor correlation or none at all. This indicated a loss of correlation between the speckle patterns recorded for the different specklegrams. Two mechanisms were suspected for this loss of correlation. The first was tilting of the burner liner sample. This would rotate the reflected field so that different portions of it are accepted by the telecentric lens aperture. The second mechanism was axial displacement of the sample which shifts the original speckle pattern to a different focal plane. Tests were performed by NASA personnel to investigate these problems as described in the previous section of this report.

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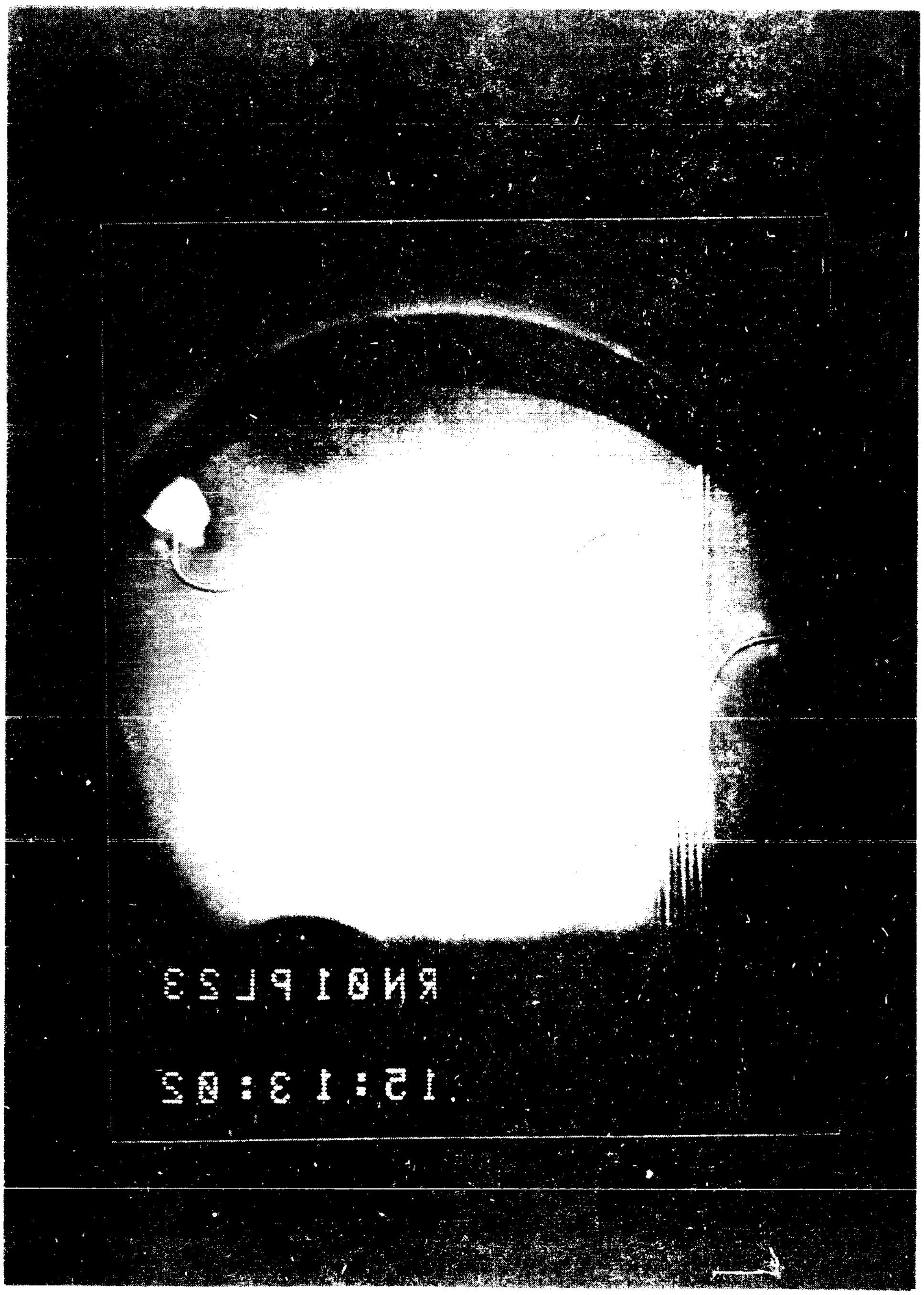
FIG. 2

OF POOR

PRINT OF A SPECKLE PHOTOGRAPH



Four pairs of specklegrams at the end of the run were observed to have good correlation at the center of the image. These were 17-19 and 19-21 at 888°C, and 18-20 and 20-22 at 126°C. When these were examined at other locations, however, it was found that there were areas of poor or no correlation, particularly at the top and bottom of the images. This indicated that the sample probably warped out of plane by a millimeter or more.

In order to be able to process the four pairs of plates, a separate array of 12 data locations were chosen for each pair of plates, except in the case of pair 19&21 where it was possible to use the same set as for 17&19. Coordinate axes were chosen such that the centers of the three straps holding the long serpentine thermocouple lead were at (-8mm,-11mm), (-1.5mm,+8mm), and (+14mm,+14mm). The pairs of plates were processed on the heterodyne photocomparator and strain results were obtained and tabulated as follows:

Plates 18 & 20

Point #	x-strain	shear	y-strain
1 (20, -9)	1734	-167.5	-42
2 (12, -9)	920	472.5	434
3 (4, -9)	374	49	1104
4 (15, -4)	1477	368	480
5 (5, -4)	-346	151.5	499
6 (-2.5,-4)	107	155	591
7 (15.5,2)	1518	8.5	674
8 (8.5,2)	1435	-178.5	1212
9 (2, 2)	-948	517	-69
10 (-2, 2)	622	-758	1561
11 (20, 8)	1603	-106	1456
12 (10, 8)	1092	3.5	1561

Plates 20 & 22

Point #	x-strain	shear	y-strain
1 (5, -15)	268	-294.5	-103
2 (-5, -15)	-883	-245	-503
3 (-15, -15)	361	436.5	-273
4 (15,-7.5)	-759	3.5	604
5 (0,-7.5)	148	113.5	678
6 (-15,-7.5)	-202	331.5	273
7 (12.5,2.5)	291	287.5	1016
8 (0 ,2.5)	500	-74	910
9 (-12.5,2.5)	-219	508.5	425
10 (19,11.5)	-319	287	387
11 (0,11.5)	-199	-825	1430
12(-12.5,8.5)	-1020	69.5	932

Plates 17 & 19

Point #	x-strain	shear	y-strain
1 (5, -15)	-131	532	-1248
2 (-5, -15)	421	-94	-858
3 (-15, -15)	-464	178	535
4 (-12.5,2.5)	-859	1317	-1677
5 (0, 2.5)	-1100	320	-1511
6 (-12.5,2.5)	224	405.5	4025
7 (-19, 11.5)	294	981.5	2093
8 (0, 11.5)	-184	88	1519
9 (-12.5,11.5)	-51	-838.5	1928
10 (10,20)	-1456	1320.5	-581
11 (0, 20)	-1561	-631.5	752
12 (-10,20)	-198	125.5	-1505

Plates 19 & 21

Point #	x-strain	shear	y-strain
1 (5,-15)	396	91	359
2 (-5,-15)	-511	-13	-192
3 (-15,-15)	963	439	72
4 (12.5,2.5)	-75	-648.5	-48
5 (0 ,2.5)	843	547	712
6 (-12.5,2.5)	-91	-61.5	-62
7 (19, 11.5)	-155	66.5	-540
8 (0, 11.5)	449	480.5	488
9 (-12.5,11.5)	-100	1040.5	967
10 (10,20)	-382	-255	-1622
11 (0, 20)	276	945	-235
12 (-10,20)	-270	386.5	756

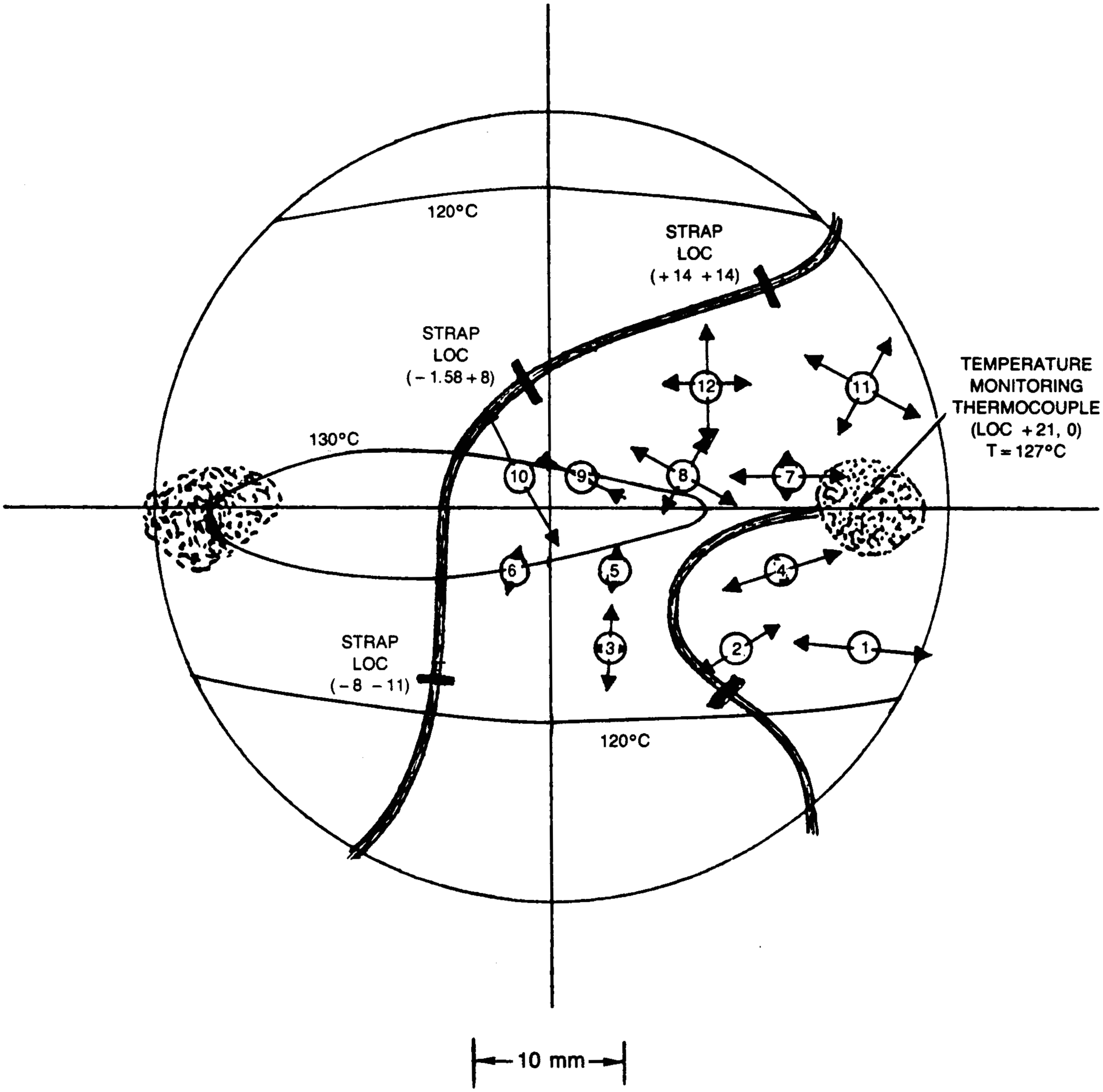
In order to present the strain patterns in a more graphic manner, the values above were resolved into principal strains and orientations. These were plotted on sketches of the photographs as shown in Figs. 3-6. The measurement locations are indicated by circled numbers and the strains are indicated by outward arrows for tensile strain and inward arrows for compressive strain. Strain magnitude is indicated by the length of the arrow. The shaded areas indicate the cement covering the bonded thermocouples. Isotherms indicate typical temperature distribution over the area of measurement.

4.2 Second Data Run Evaluation

After the sample was fastened more securely in the burner liner cyclic rig a second run identical to the first was performed. Specklegrams from the second run were delivered to UTRC for analysis. It was determined that about

STRAIN DISTRIBUTION FROM RUN NO. 1

PLATES 18 AND 20



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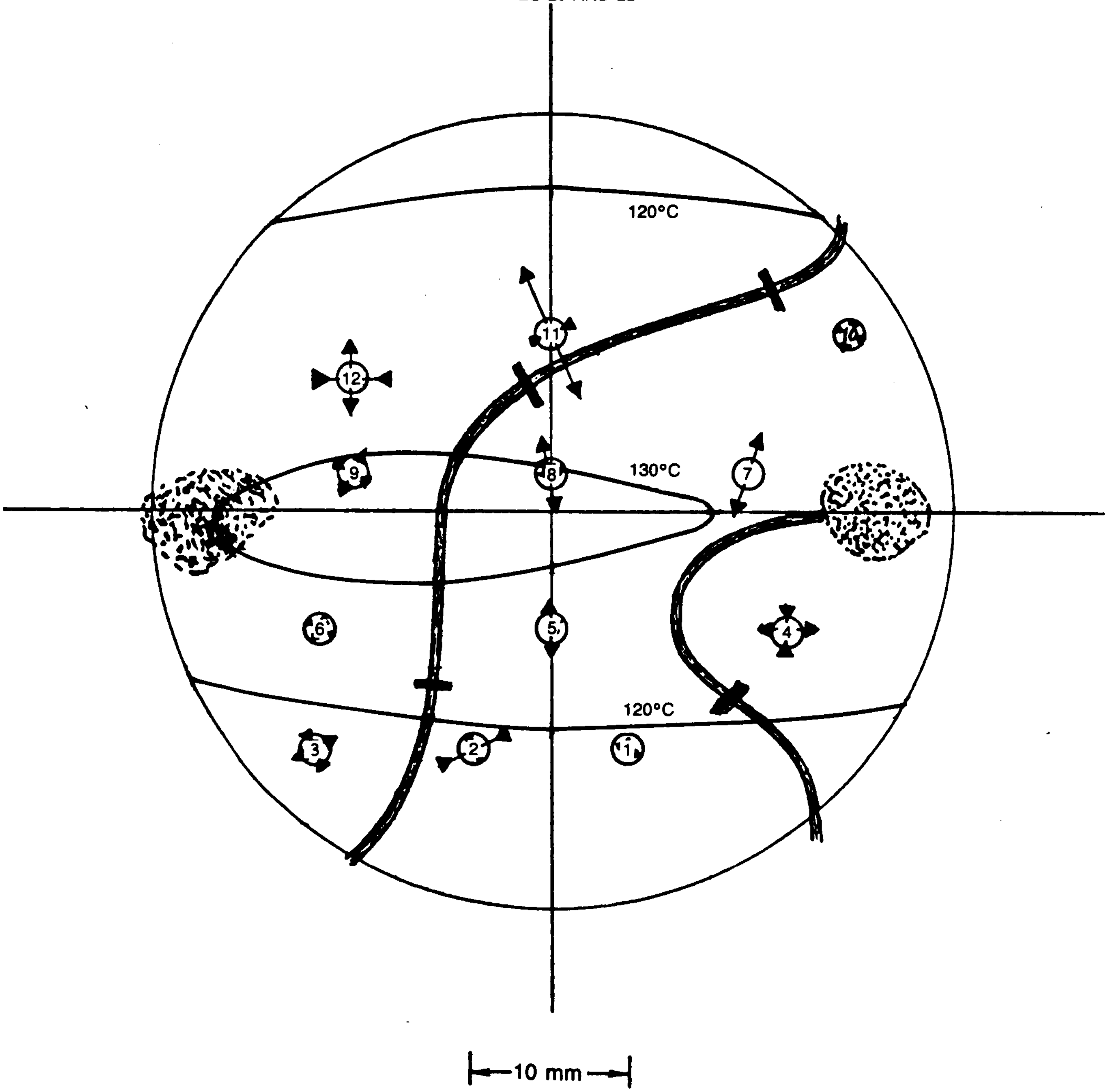
STRAIN DISTRIBUTION FROM RUN NO. 1

PLATES 20 AND 22



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STRAIN DISTRIBUTION FROM RUN NO. 1

PLATES 17 AND 19

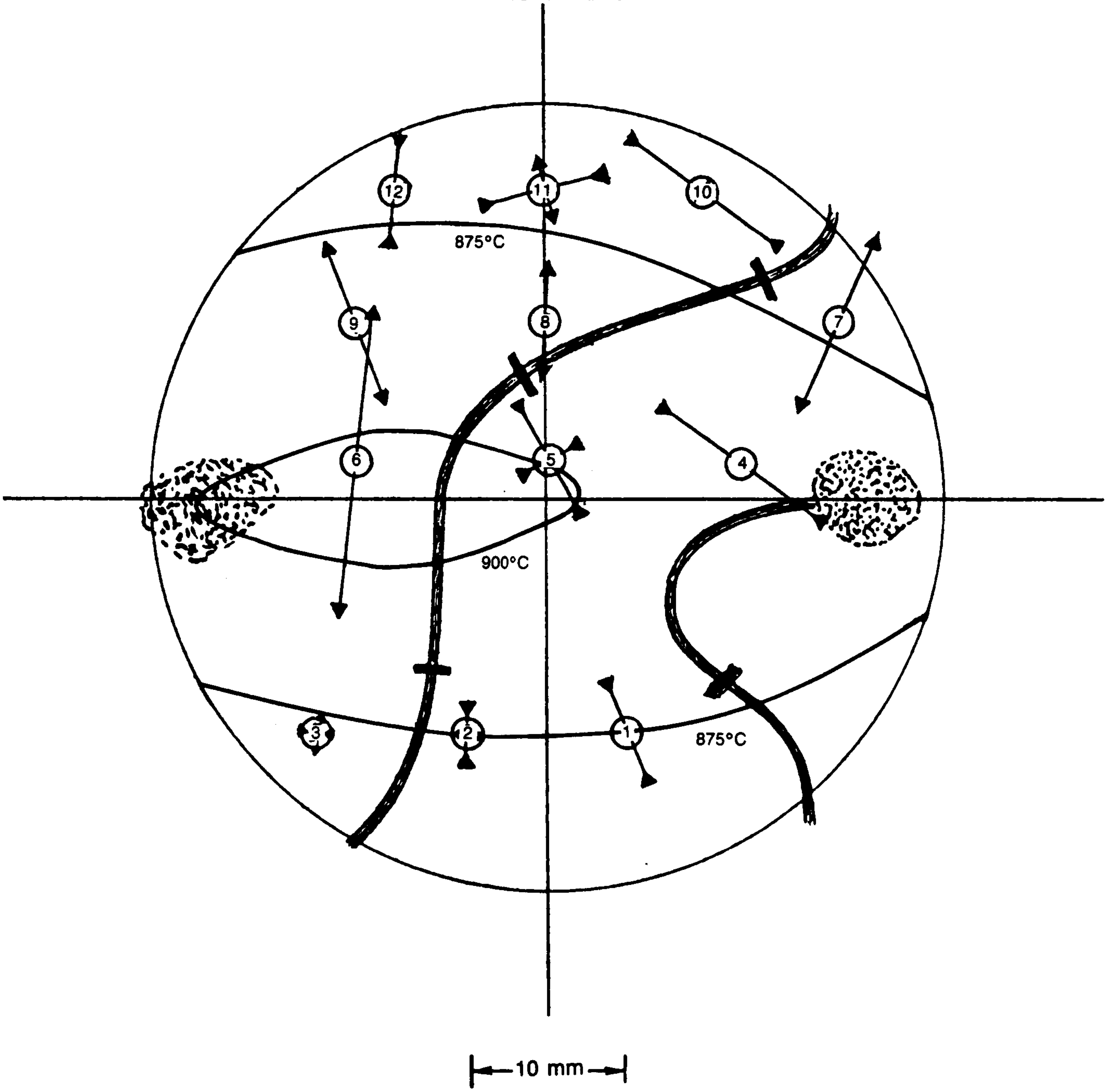

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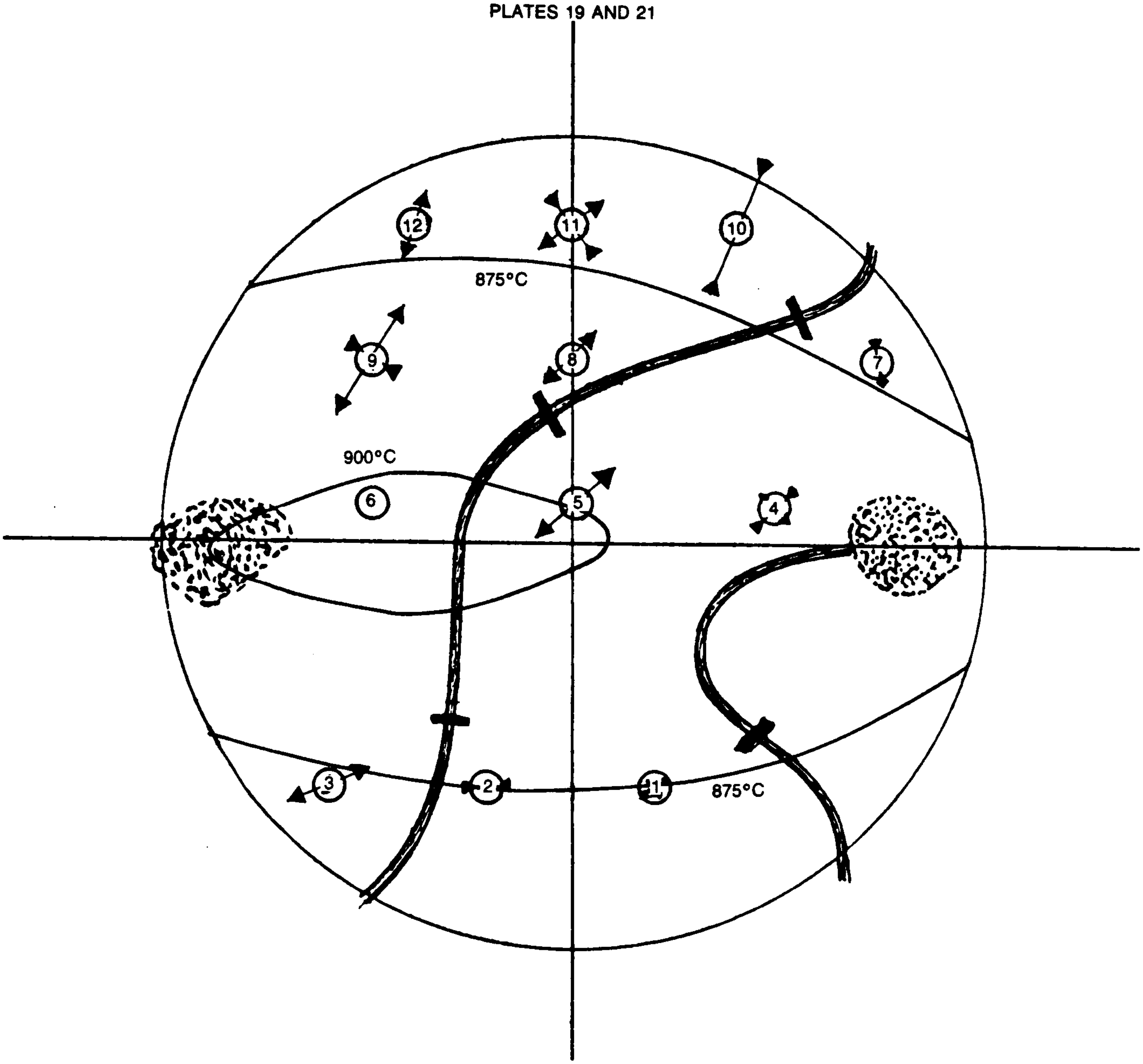
FIG. 6

STRAIN DISTRIBUTION FROM RUN NO. 1

PLATES 19 AND 21



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six pairs of plates had sufficient correlation in some areas to allow data reduction. This was deferred, however, in favor of performing a third run where the temperature increments would be reduced to enhance correlation.

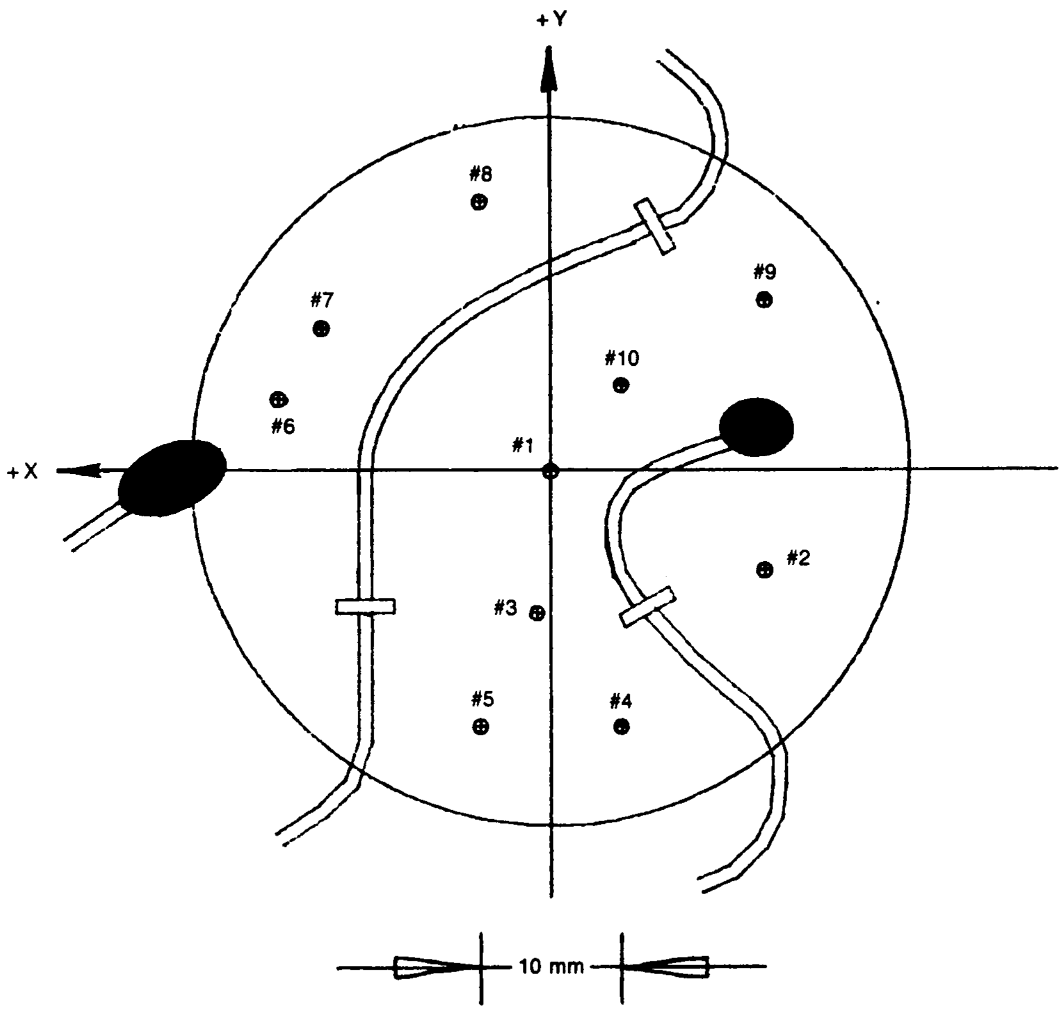
4.3 Third Data Run Evaluation

A third data run was performed by personnel at NASA Lewis Research Center, and the developed plates were shipped to UTRC for evaluation. On this run the temperature increments were made smaller than on the previous runs in hope of reducing the problems due to tilting and warping of the sample plate. Inspection of the plates revealed that, although the correlation was generally better than with the larger temperature increments, there were still problems with decorrelation. A meeting was held at UTRC with NASA personnel to discuss the problems of reducing data from these specklegrams. It was decided to select ten locations on the new photographs, distributed around the usable area, and to evaluate strain at those locations for all pairs of photographs. Any locations on a pair of photographs that failed to yield good correlation would be dropped from the analysis. This approach maximized the possibility of maintaining continuity between data points. It was also decided not to process the data from the second run. Processing of the plates from the third data run yielded the following results for principle x-strain, principle y-strain, and the angle (in degrees) of the principle x-strain axis to the x axis of the plate:

Plates #3 & #5: 204°C 204°C (12:14:10 - 12:28:40)

Position x, y	Angle	x-strain	y-strain
0, 0 (#1)	-19	-269	-728
-15, -7 (#2)	42	-1065	116
1,-10 (#3)	-16	-531	948
-5,-18 (#4)	-31	-91	1930
5,-18 (#5)	-32	-284	135
19, 5 (#6)	18	109	-337
16, 10 (#7)	-28	254	-38
5, 19 (#8)	-36	-387	962
-15, 12 (#9)	-7	-968	-58
-5, 6(#10)	9	1359	-672

LOCATION OF DATA POINTS FOR RUN #3



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Plates #2 & #23: Ambient - Ambient (10:39:55 - 13:51:51)

Position x, y	Angle	x-strain	y-strain
0, 0 (#1)	-6	-58	231
-15, -7 (#2)	-16	606	20
1,-10 (#3)	-28	-895	92
19, 5 (#6)	9	167	-292
-15, 12 (#9)	-36	-177	329
-5, 6(#10)	-14	103	533

Plates #4 & #6: 899°C-899°C (12:20:53 - 12:34:31)

Position x, y	Angle	x-strain	y-strain
0, 0 (#1)	31	794	-88
-15, -7 (#2)	29	-414	-799
1,-10 (#3)	-37	738	-535
-5,-18 (#4)	16	-549	401
5,-18 (#5)	-36	-86	2392
19, 5 (#6)	-11	545	-726
16, 10 (#7)	39	32	-339
5, 19 (#8)	-41	-778	-158
-15, 12 (#9)	-17	-1161	-564
-5, 6(#10)	21	976	-774

Plates #7 & #8: 649°C-704°C (12:40:01 - 12:42:51)

Position x, y	Angle	x-strain	y-strain
0, 0 (#1)	-13	-110	1073
-15, -7 (#2)	25	-540	777
1,-10 (#3)	41	1792	348
-5,-18 (#4)	35	525	206
-5, 6(#10)	3	1522	2244

Plates #8 & #9: 704°C-760°C (12:42:51 - 12:45:26)

Position x, y	Angle	x-strain	y-strain
0, 0 (#1)	-18	1651	1224
-15, -7 (#2)	-4	2027	-709
1,-10 (#3)	26	1841	-499
16, 10 (#7)	-39	928	-348
5, 19 (#8)	12	1805	915
-15, 12 (#9)	9	2443	1366
-5, 6(#10)	-2	1272	118

Plates #9 & #10: 760°C-816°C (12:45:26 - 12:47:55)

Position x, y	Angle	x-strain	y-strain
0, 0 (#1)	-25	207	1161
5, 19 (#8)	-2	-93	-630
-15, 12 (#9)	-37	-699	2090
-5, 6(#10)	-38	1150	2389

Plates #11 & #12: 843°C-857°C (12:50:12 - 12:56:06)

Position x, y	Angle	x-strain	y-strain
-15, -7 (#2)	-20	-118	-1869
1,-10 (#3)	40	-331	277
19, 5 (#6)	33	-2595	907
16, 10 (#7)	-24	45	-2268
5, 19 (#8)	-39	1668	-1320

Plates #14 & #15: 885°C-899°C (13:05:57 - 13:08:37)

Position x, y	Angle	x-strain	y-strain
0, 0 (#1)	-19	1109	276
-5,-18 (#4)	-32	1482	-964
19, 5 (#6)	-44	1522	663
-5, 6(#10)	4	680	-2852

Plates #15 & 16: 899°C-885°C (13:08:37 - 13:11:55)

Position x, y	Angle	x-strain	y-strain
0, 0 (#1)	-8	-991	396
5,-18 (#5)	10	-236	-1803
19, 5 (#6)	28	-2183	113
16, 10 (#7)	33	-2221	2100
5, 19 (#8)	-36	-598	-1873
-15, 12 (#9)	17	413	-221

Plates #16 & #17: 885°C-871°C (13:11:55 - 13:14:13)

Position x, y	Angle	x-strain	y-strain
1,-10 (#3)	-23	592	-251
-5,-18 (#4)	-23	-543	2063
5,-18 (#5)	25	-61	1716
19, 5 (#6)	23	926	-828
16, 10 (#7)	40	1604	-546
-15, 12 (#9)	-4	214	899

Plates #17 & #18: 871°C-857°C (13:14:13 - 13:15:51)

Position x, y	Angle	x-strain	y-strain
0, 0 (#1)	43	142	2546
5,-18 (#5)	-1	-651	409
19, 5 (#6)	-35	2484	91
-15, 12 (#9)	39	279	1073
-5, 6(#10)	-38	880	522

Plates #18 & 19: 857°C-843°C (13:15:51 - 13:18:03)

Position x, y	Angle	x-strain	y-strain
0, 0 (#1)	25	383	-127
16, 10 (#7)	9	-1464	-668
-5, 6(#10)	6	-754	-198

Plates #19 & #20: 843°C-816°C (13:18:03 - 13:20:20)

Position x, y	Angle	x-strain	y-strain
0, 0 (#1)	25	-749	-1722
-15, -7 (#2)	-41	505	-103
19, 5 (#6)	25	-1117	-2369
16, 10 (#7)	-17	615	1224
-5, 6(#10)	44	1482	-728

4.4 Return of the Specklegram Recording System

The specklegram recording system was packed and shipped back to UTRC, and the equipment arrived in excellent condition. The pulsed ruby laser head was disassembled for inspection, and corrosion was found on the ground strap to the flash lamp. This accounted for difficulties experienced in firing the laser during the second and third runs. The corrosion was traced to a steel set screw in a brass fitting which was replaced with a brass screw.

5.0 DISCUSSION

The data obtained in this series of tests shows a very erratic pattern of strain. This is particularly true for the data obtained by comparison of the sample before and after a temperature cycle. The important question is whether this data is a valid description of the strain induced in the sample as a result of the thermal cycling or whether it is the result of turbulence or other artifacts of the specklegram recording system. To determine this would require comparison of two speckle photographs recorded one after the other with no change in the operating conditions. Unfortunately no such pair was recorded on the last run, which had the best data. The next best comparison is to examine the strain at one location as a function of temperature in run #3 to see if the thermal expansion is evident. In order to select a point at which to make this comparison, it is helpful to tabulate the valid data points in table 1 as follows:

Pair	1	2	3	4	5	6	7	8	9	10
7&8	x	x	x	x	-	-	-	-	-	x
8&9	x	x	x	-	-	-	x	x	x	x
9&10	x	-	-	-	-	-	-	x	x	x

11&12	-	x	x	-	-	x	x	x	-	-

14&15	x	-	-	x	-	x	-	-	-	x
15&16	x	-	-	-	x	x	x	x	x	-
16&17	-	-	x	x	x	x	x	-	x	-
17&18	x	-	-	-	x	x	-	-	x	x
18&19	x	-	-	-	-	-	x	-	-	x
19&20	x	x	-	-	-	x	x	-	-	x

TABLE 1. Valid Data in the Third Data Run. x indicates a valid strain data point and - indicates no data available, and the dashed lines indicate lack of correlation.

This table shows that whereas point #1 (at the center of the field of view) yielded the largest number of valid data points overall, point #6 yielded the largest number of consecutive data points, i.e. the 4 points from plate #14 to plate #18. In order to examine the accumulated strain between these four conditions the strains must be added, and to do this they must be expressed in a common coordinate system, for example the coordinates of the plate. The results of this are tabulated in table 2.

Temp °C	x-strain	shear	y-strain	Thermal Expansion
885°C	---	---	---	
899°C	1108	429	1077	224
885°C	-563	1384.5	678	0
871°C	94	753	119	-224
857°C	1800	1873	988	-448

TABLE 2. Strain at Point #6 as a Function of Temperature. To the right is the expected thermal expansion based upon one thermocouple reading.

Table 2 shows an erratic pattern of strain at point #6 as a function of temperature with very little correlation to the expected thermal expansion. The measured strain values may be influenced by changing temperature patterns on the sample, however, it is difficult to imagine that they could be so significant over 14°C temperature increments as to create the stresses required for 1000 to 2000 microstrain deformations.

6.0 CONCLUSIONS

It has been demonstrated that speckle photogrammetry can be accomplished on a burner cyclic fatigue rig involving transportation of the specklegram recording system. Difficulties were encountered with out-of-plane warping of the sample, and post test examination of the sample showed plastic deformation in the order of 1 cm. Means must be found to control this deformation in any further applications. Tilting and out-of-plane deformation may be less with a rig designed to test a cylindrical section of burner liner material. This is because a cylindrical shell should be less sensitive to out-of-plane bowing than a flat sample when the center is heated. The following are recommendations with regard to follow-on work for the application of this technique.

1. Measurement of out-of-plane deformation. A technique should be developed for measurement of out-of-plane deformation of samples in the burner liner cyclic fatigue rig. If suitably accurate measurements of out-of-plane deformation are made, the effects of various methods of heating and constraining the sample can be studied to determine which are most compatable with speckle photogrammetry.

2. Study of the sensitivity of speckle photogrammetry to tilt and out-of-plane deformation. Studies should be performed to determine the exact nature of the sensitivity of speckle photogrammetry to tilt and out-of-plane deformation. The limits these motions impose on this technique are postulated on theoretical considerations because no systematic study of these effects has been conducted. An experimental study of the effect of these motions on halo correlation will provide a basis for evaluating its aplicability to specific measurement problems. Such a study is also essential to finding an ultimate cure for these difficulties.

3. Study of high-temperature white-light speckle photogrammetry. Sensitivity to surface tilting can be eliminated if the laser speckles are replaced with a real random structure on the surface of the object. Research studies at UTRC have shown that photographs of retroreflective paint, bonded to an object, can be used for strain measurements with accuracies approaching 100 microstrain. Such beads can be used up to nearly 500°C, and it may be possible to find materials that could work at higher temperatures. Although this technique would be sensitive to defocusing due to out-of-plane deformation, it could make measurements possible where tilting was the primary problem.

4. Studies of the basic accuracy of speckle photogrammetry. Studies should be conducted on the basic accuracy of speckle photogrammetry when it is operating on a burner rig. During this test, pairs of photographs should have been taken at various steady-state operating conditions which would have theoretically yielded zero strain values when processed. Processing of such data would have yielded a measure of the basic accuracy of the technique in the test rig environment as a function of operating temperature and air flow. To date, only laboratory test have been used to characterize this strain measurement technique.

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