Comparison Testings between Two High-temperature Strain Measurement Systems

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ABSTRACT—An experimental evaluation was conducted at NASA Lewis Research Center to compare and contrast the performance of a newly developed resistance strain gage, the PdCr temperature-compensated wire strain gage, to that of a conventional high-temperature extensometry. The evaluation of the two strain measurement systems was conducted through the application of various thermal and mechanical loading spectra using a high-temperature thermomechanical uniaxial testing system equipped with quartz lamp heating. The purpose of the testing was not only to compare and contrast the two strain sensors but also to investigate the applicability of the PdCr strain gage to the testing environment typically employed when characterizing the high-temperature mechanical behavior of structural materials. Strain measurement capabilities to 800°C were investigated with a nickel base superalloy IN100 substrate material, and application to titanium matrix composite (TMC) materials was examined with the SCS-6/Ti-15-3 $[0]_8$ system. PdCr strain gages installed by three attachment techniques—namely, flame spraying, spot welding and rapid infrared joining—were investigated.

Introduction

Conventional high-temperature extensometry is often used in industrial and research laboratories to either monitor or control strain levels of the materials on the coupon level. When considering the more expensive and critical testing of larger subcomponent specimens or full-scale components, there is, however, a great need for elevated temperature strain gages, since the use of extensometry is often not viable or is highly impractical. In response to the needs, an advanced PdCr/Pt dual-element resistance strain gage was recently developed at NASA Lewis Research Center (LeRC). This wire gage is temperature-compensated and exhibits desirable properties and a relatively small and repeatable apparent strain to 800°C.[1-2] Since its introduction, the PdCr resistance strain gage has been demonstrated as a viable high-temperature strain sensor on several monolithic superalloys and a titanium matrix composite (TMC) system. However, given the relative complexities of the desired testing for large components, and the complications introduced when interpreting high-temperature composite behavior, a much more detailed characterization and analysis is needed.

A detailed experimental evaluation was therefore conducted at NASA LeRC to compare and contrast the performance of the PdCr temperature-compensated wire resistance strain gage to that of a conventional high-temperature extensometer. The evaluation of the two strain measurement systems was conducted through the application of various thermal and mechanical loading spectra using a high-temperature thermomechanical uniaxial testing system. This was done not only to compare and contrast the two strain sensors but also to investigate the applicability of the PdCr strain gage to the coupon-level specimen-testing environment typically employed when characterizing the high-temperature mechanical behavior of structural materials. Strain measurement capabilities to 800°C were investigated with a nickel base superalloy (IN100) substrate material, and application to TMCs was examined with the model system SCS-6/Ti-15-3. Three gage installation techniques were applied and investigated in this comparison study; namely, flame spraying, spot welding and rapid infrared joining.

Test Specimens and Setup

The test specimens used in this study consisted of three IN100 and three SCS-6/Ti-15-3 $[0]_8$ coupons with a nominal geometry of 200 mm × 25 mm × 2-3 mm (l × w × t). One of each material system was instrumented with PdCr wire strain gages installed using a flame-spraying technique. A flame-sprayed gage is a free-filament PdCr wire strain gage installed directly to the specimen surface, as shown in Fig. 1, by flame spraying various coatings of nickel-aluminide, alumina, and alumina-zirconia.[4] The second specimen for each material system was instrumented with weldable PdCr gages. A weldable gage is a gage initially flame sprayed on a metal carrier which is subsequently spot welded to the test specimen, as shown in Fig. 2. For some field applications where environmental factors, size of test articles and time requirements preclude the use of the flame-sprayed gage, a weldable gage offers an advantage. Hastelloy X and TIMETAL 21S shims with thickness of 75 micron were used in this study as the metal carriers for the IN100 and SCS-6/Ti-15-3 $[0]_8$ specimens, respectively. The TIMETAL 21S shim was heat treated in a vacuum at 621°C for eight hours for phase stabilization before gaging. Although the weldable gage can be easily applied, it has limitations such as the stiffening effect and the stress concentrations at the welds. In addition, the weld-

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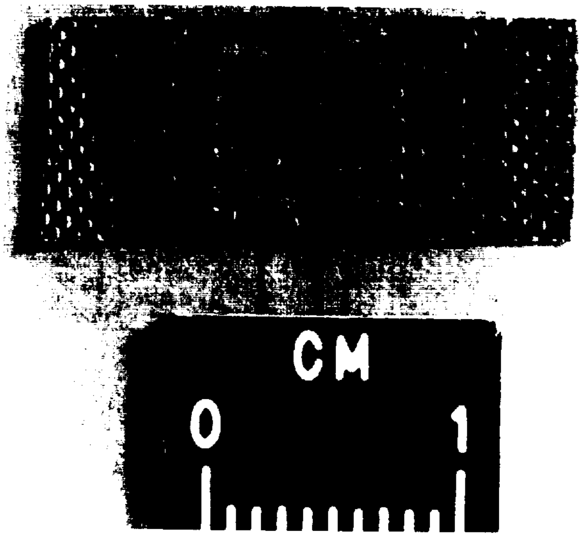

Fig. 1—PdCr temperature-compensated wire strain gage taped on a specimen with frame-sprayed base coat

Fig. 2—A weldable PdCr wire strain gage on an IN100 specimen tested with an extensometer

able gage can only be applied to weldable base materials. A third installation technique is therefore being studied as an alternative gage installation technique.[3] This technique, the rapid infrared joining (RIJ) process, can be applied to all substrate materials and has the potential to be applied

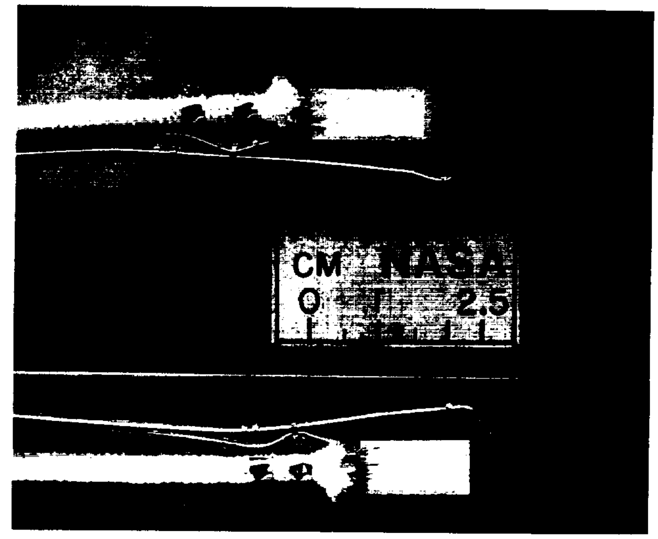

Fig. 3—A rapid infrared-joined PdCr wire strain gage (top) and a flame-sprayed PdCr wire gage (bottom) on a TMC specimen

in the test field. It was used to install the PdCr wire gages on the third specimen of each material system. A RIJ gage was a gage first flame sprayed on a metal carrier, which was subsequently infrared joined to the test specimen. Since the RIJ gages installed on the IN100 specimen delaminated after the gaging process, no test results were obtained and therefore none will be reported. Only the gaging process on the TMC will be described here.

The surface of the SCS-6/Ti-15-3 $[0]_8$ coupon was first polished to a 17-micron finish to remove any surface oxides. A 34-micron brazing foil with a composition of Ti-15Cu-15Ni wt percentage was utilized as the joining filler. The filler was of the rapidly solidified type and had a solidus of 902°C and a liquidus of 932°C during transient heating. The filler material was cut to the exact dimensions of the TIMETAL 21S carrier and inserted between the carrier and the Ti-15-3 specimen. The gage back, base material and filler material were degreased with acetone. A carbon fixture and carbon screws were utilized to apply minimal pressure to the gage in order to maintain placement during joining. The assembly was then placed in the infrared furnace where argon was continually purged through the heating chamber at 250 ml/min in order to prevent oxidation. The temperature of the specimen was brought to the joining temperature, 1100°C, in 20-30 s and held at that temperature for 300 s to produce isothermal solidified and homogenized joints. Upon completion of the joining, termination of the infrared allows for a rapid cooling, 8°C/s to 600°C. The rapid cooling is due to the cold wall process in which only the sample is heated to the joining temperature. The joining parameters utilized were extracted from a thin film diffusion model, fiber reaction zone growth mode and experiment verification.[3] The RIJ-gaged specimen was heat treated in a vacuum at 700°C for 12 hours before testing to restabilize the TMC substrate material. Figure 3 presents a RIJ gage installed on a TMC specimen in comparison to a flame-sprayed gage.

The test setup consisted of a uniaxial, servo-hydraulic loading frame typically used for thermomechanical fatigue

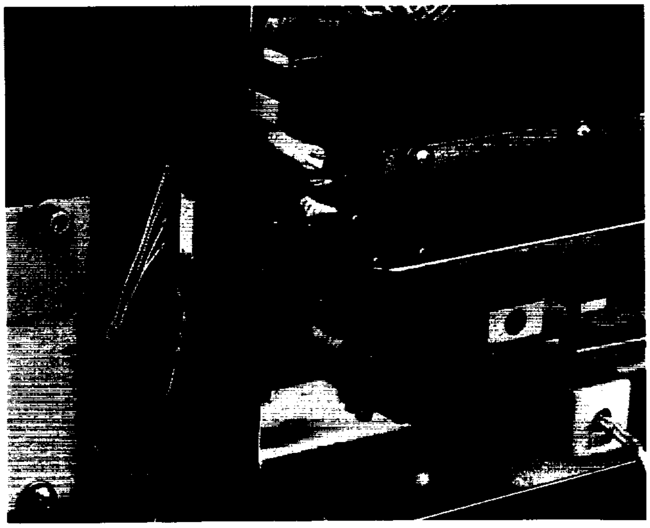

Fig. 4—Thermomechanical loading system with quartz lamp heating system

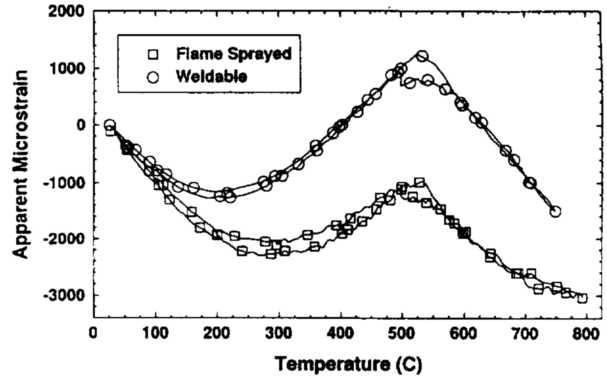

Fig. 5—Apparent strain characteristics of a flame-sprayed and a weldable PdCr wire strain gage mounted on IN100 specimens

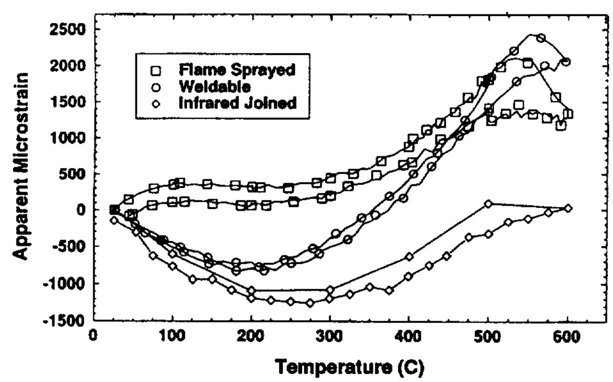

Fig. 6—Apparent strain characteristics of a flame-sprayed, a weldable and a rapid infrared-joined PdCr wire strain gage on a SCS-6/Ti-15-3 $[0]_8$

(TMF) testing. A radiant quartz lamp heater was used for specimen heating, and intrinsic K-type thermocouples were used to monitor and control temperature. Water-cooled wedge grips were used for specimen gripping. The extensometer is a commercially available air-cooled resistance-based extensometer with a gage section of 12.7 mm (distance between probes). This device was mounted on the thickness edge of the specimen in contrast to the strain gages, which are mounted on the face of the specimen width (see Fig. 4).

Results and Discussion

The temperature-induced apparent strain of the PdCr gages installed with all three techniques were found to be repeatable between thermal cycles on both the IN100 and the SCS-6/Ti-15-3 $[0]_8$ as shown in Figs. 5 and 6. The apparent strains of the gages on IN100 were repeatable to approximately ±100 microstrain between heat-up to 800°C and cool-down to room temperature, while the apparent strains of the gages on SCS-6/Ti-15-3 were repeatable to approximately ±150 microstrain between heat-up to 600°C and cool-down to room temperature. Note that each gage exhibited some uniqueness with respect to the apparent strain characteristics. This resulted from the different thermal histories the gages experienced during the gaging processes and the difference in differential thermal expansion between the gage and the specimen material. It was also related to the fact that the temperature gradient over the gage section was slightly different for each specimen.

The temperature-induced signal (apparent strain) of a resistance strain gage is caused by two effects: the change in gage resistance with change in temperature, and the differential thermal expansion between the gage and the test specimen to which the gage is bonded. On the other hand, the temperature-induced signal (thermal strain) that an extensometer measures is purely from the thermal expansion of the test specimen. For example, the temperature-induced apparent strain of a PdCr weldable gage on the IN100 was within ±1000 microstrain in the temperature range from room temperature to 800°C, while the temperature-induced thermal strain of the IN100 that the extensometer measured was approximately 12000 microstrain ($\mu\varepsilon$). In order to have a true comparison in thermal strain measurements, one IN100 specimen was instrumented with both an attached and floating weldable strain gage. Knowing the thermal expansion of the gage carrier and by measuring the difference in output of these two gages, the thermal expansion strain of the specimen can be calculated. This calculated data, as shown in Fig. 7, exhibited excellent agreement with that measured by the high-temperature extensometry.

As for the mechanical response, the gages and extensometer on both the IN100 (Figs. 8 and 9) and SCS-6/Ti-15-3 (Figs. 10-12) were in relatively good agreement over the temperature ranges examined. Note that both the extensometer and PdCr gages indicated that TMCs experienced some permanent strain when mechanical cycled at 600°C,

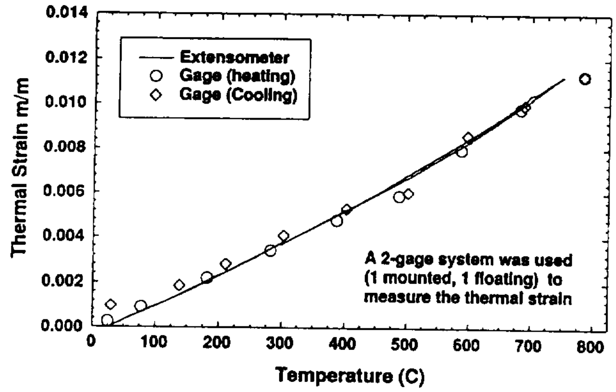

Fig. 7—Thermal expansion induced strain of IN100 measured by extensometer and weldable PdCr wire strain gage

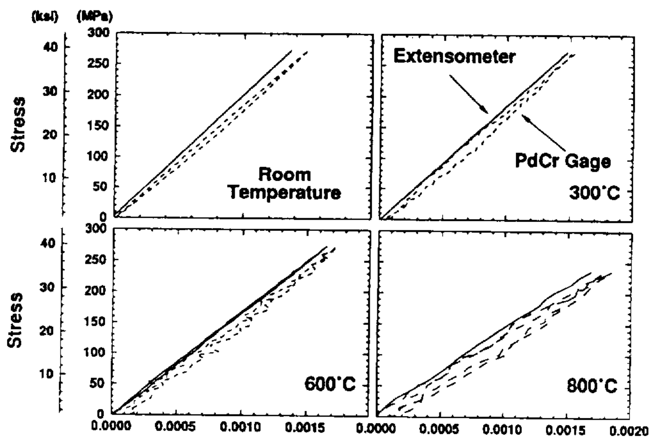

Fig. 8—Stress-strain response of extensometer and flame-sprayed PdCr wire gage on IN100

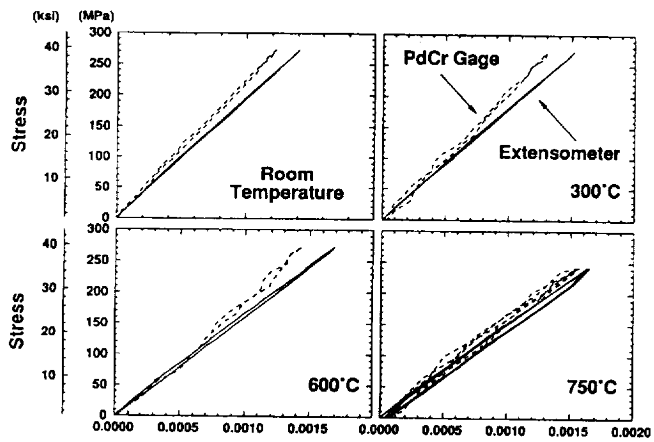

Fig. 9—Stress-strain response of extensometer and weldable PdCr wire gage on IN100

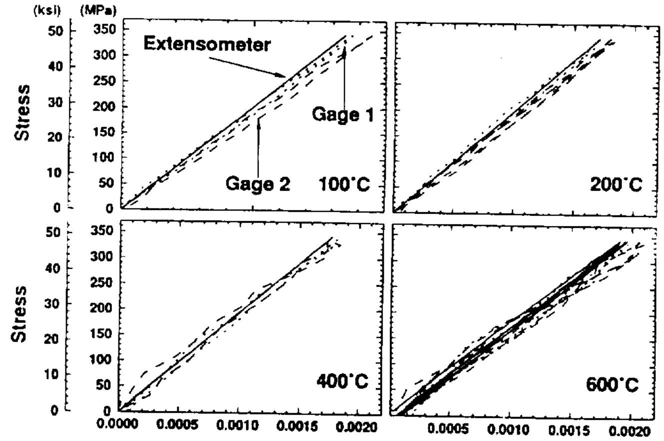

Fig. 10—Stress-strain response of extensometer and flame-sprayed PdCr wire gage on SCS-6/Ti-15-3 $[0]_8$

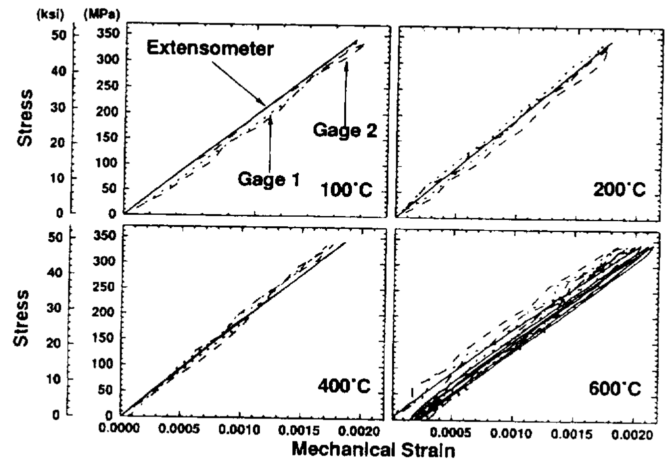

Fig. 11—Stress-strain response of extensometer and weldable PdCr wire gage on SCS-6/Ti-15-3 $[0]_8$

as noted in Figs. 10-12. A slightly larger variation was found in the low-temperature measurements with the weldable gage as shown in Fig. 9. This suggests the need for premechanical cycling of the weldable gage at the maximum operating temperature before actual testing. The testing with the RIJ gages was limited to 1000 microstrain, because the gages responded nonlinearly at higher load. The cause of the nonlinearity is still yet to be determined. The calculated stiffness from the test results shown in Figs. 8-12 is shown in Figs. 13 and 14 for the IN100 and the TMC, respectively. The variations between the extensometer and gages were within 10 percent over the temperature range examined.

After all the mechanical loading cycles, the specimens were subjected to thermal cycles again to measure changes in the apparent strain responses. The apparent strain responses of both the weldable and flame-sprayed gages on IN100 and TMC were repeatable before and after the mechanical testings, as shown in Figs. 15 and 16. The gages

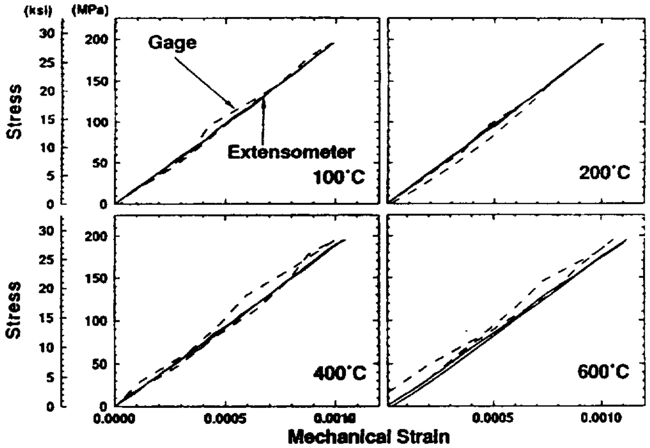

Fig. 12—Stress-strain response of extensometer and rapid infrared-joined PdCr wire gage on SCS-6/Ti-15-3 $[0]_8$

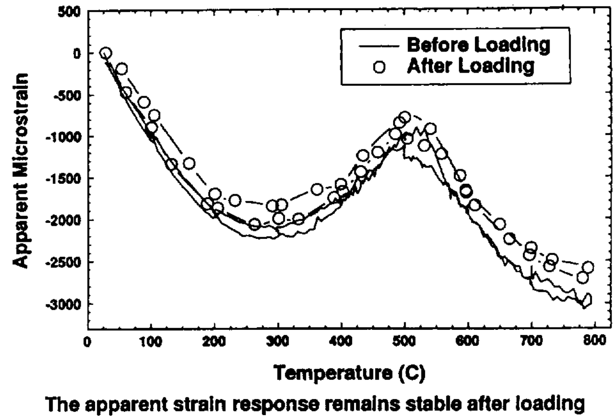

Fig. 15—Apparent strain characteristics of flame-sprayed gages on IN100 before and after mechanical loading

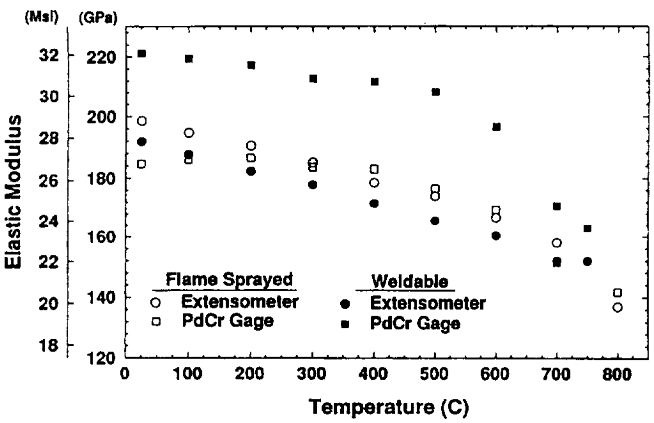

Fig. 13—Comparison of calculated stiffness for IN100 specimens

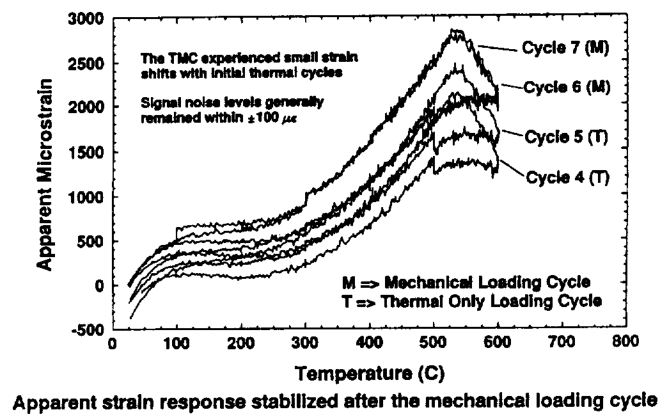

Fig. 16—Apparent strain characteristics of flame-sprayed gages on SCS-6/Ti-15-3 $[0]_8$ before and after mechanical loading

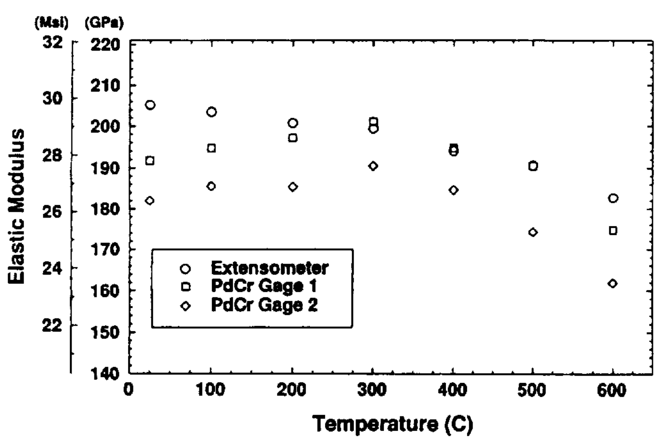

Fig. 14—Comparison of calculated stiffness for SCS-6/Ti-15-3 $[0]_8$ specimen

mounted on the IN100 specimens tended to show a repeatable apparent strain in the very first cycle, since the thermal response of the IN100 was stable. This was not the case, however, for the TMC material, as shown in Fig. 16. These progressive changes in the apparent strain behavior of the gages on the TMC were corroborated by the extensometer, which was measuring the change in the material's thermal strain response with changes in temperature. Also, the TMC specimen was found to be slightly warped after testing. Given this TMC behavior, care must be taken in interpreting elevated temperature strain gage results from a material which can potentially experience changes in thermal strain behavior.[4] If the thermal strain response of the material changes and causes a change in the apparent strain response of the gage, one will not be able to distinguish between thermal and mechanical strains.

Subsequent to the thermal and mechanical testing, the specimens were subjected to progressively increasing me-

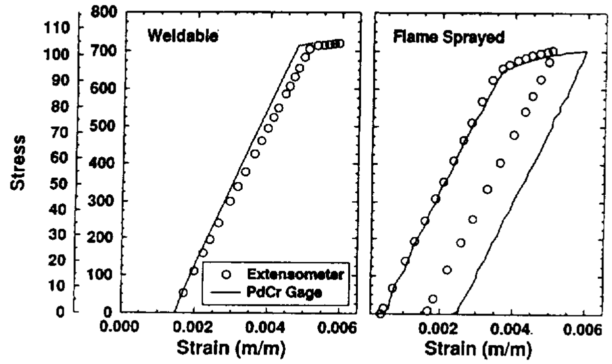

Fig. 17—Mechanical loadings to determine strain limit of PdCr wire strain gage at room temperature

chanical loads to measure the maximum mechanical strain threshold of the gages at room temperature; these data are shown in Fig 17. The gages tended to lose reliable strain measurement capabilities at approximately 4500 με. It is noteworthy to point out that the flame-sprayed gages did not fail catastrophically; rather, they continued to read linearly and for the most part accurately at strains below this level subsequent to the overload to 4500 με. The weldable gage experienced a failure related to the delamination of the metal carrier from the test specimen.

Conclusions

An experimental evaluation with conventional high-temperature extensometry suggested that the newly developed PdCr temperature-compensated wire strain gage can be successfully used as a strain-monitoring device in a coupon-level thermomechanical loading system equipped with quartz lamp heating. The apparent strain responses of gages installed by the three different techniques investigated were all repeatable on both the IN100 and SCS-6/Ti-15-3 $[0]_8$. However, the TMC specimens required a few thermal cycles prior to establishing a repeatable thermal response. Thermal expansion induced strain measurements showed excellent agreement between the extensometry and PdCr strain gage to 800°C. The mechanical strain measured by two strain sensors on both the IN100 (to 800°C) and TMC (to 600°C) were in good agreement (within 10 percent) to 2000 με. A slightly larger variation was found in the low-temperature measurements with the weldable gage. The strain limit of the PdCr flame-sprayed and weldable wire gage at room temperature is approximately 4500 με, while the strain limit of RIJ gages is currently limited to 1000 με. As for future work, the comparisons/evaluations will be extended to include transverse strain measurements.

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