Defense Systems Information Analysis Center

DSIAC TECHNICAL INQUIRY (TI) RESPONSE REPORT

Use of Negative Coefficient of Thermal Expansion (NCTE) Materials in Military Sensing

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ABOUT DSIAC

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DSIAC serves as the national clearinghouse for worldwide scientific and technical information for weapon systems; survivability and vulnerability; reliability, maintainability, quality, supportability, and interoperability; advanced materials; military sensing; autonomous systems; energetics; directed energy; and non-lethal weapons. We collect, analyze, synthesize, and disseminate related technical information and data for each of these focus areas.

A chief service of DSIAC is free technical inquiry (TI) research, limited to 4 research hours per inquiry. This TI response report summarizes the research findings of one such inquiry. For more information about DSIAC and our TI service, please visit www.DSIAC.org.

ABSTRACT

The Defense Systems Information Analysis Center was asked to review information on a new metal/alloy with a negative coefficient of thermal expansion (NCTE) and offer recommendations for potential use in military sensing. The material is one of the only NCTE metals, has desirable qualities for application to sensors based on fiber-optics and photonics, and retains its properties over a broad temperature range. The material has many advantageous characteristics, but many NCTE materials/composites already exist and used in this area. The demand for a new material may be low, unless other factors increase the desirability of the product (e.g., the material could be scaled to production quantities and sold at a very low price point). Information was provided on potential product areas where the material could be used, potential U.S. Department of Defense agencies that would most likely be interested in the product, and on the use of NCTE materials in several areas. The areas include fiber-optic and photonic sensors, metamaterials (architected materials), sensors based on superconductor technology, and composite material systems.

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1.0 TI Request

1.1 SUBJECT: Negative Coefficient of Thermal Expansion (NCTE) Material use in Military Sensing

1.2 DESCRIPTION

The inquirer requested a review of information addressing the following question: Would a metal having a NCTE be of interest in military sensing, and, if so, what areas would the metal be advantageous to in design? The inquirer provided several documents for review to help answer this question.

2.0 TI Response

Defense Systems Information Analysis Center (DSIAC) subject matter experts (SMEs) in military sensing from the Georgia Technical Research Institute (GTRI) reviewed information on the material provided by the inquirer. A GTRI military sensing SME provided an assessment of metals/alloys with a NCTE for potential application to military sensing and an evaluation of U.S. Department of Defense (DoD) agencies likely to be interested in the material [1].

2.1 NEED FOR NCTE MATERIALS IN MILITARY SENSING

The GRTI SME had extensive experience working on military sensor and research development programs, some that required the development and use of negative thermal expansion (NTE) materials. In the SME's experience, thermal expansion/contraction is particularly problematic and can plague sensor systems based on fiber optics and photonics due to imparted phase noise.

The SME indicated that, ideally, expansion/contraction issues would be resolved by employing materials with near-zero thermal expansion. Alloys with near-zero thermal coefficient could facilitate the fabrication of sensors based on optical fiber, photonics, and superconducting coils. For these types of sensors, NTE materials could be used as coatings, bobbins, mandrels, and/or packaging materials. However, the demand for a new NTE metal alloy in the military sensing area would be low. Numerous NTE materials already exist and are available for sensor systems.

The demand for new NTE could increase if the cost of the materials was significantly lower than existing competing materials. Additionally, any production quantity demand for the new material would likely be at the sensor original equipment manufacturer level (driven by commercial and defense requirements) and not directly within the DoD itself.

Possible applications for materials with an NCTE in the military sensing area identified by the SME included the following:

1. Fiber-optic and photonic sensors:
    a. Temperature change compensation in fiber Bragg grating (FBG) sensors and long period fiber gratings
    b. Fiber-optic acoustic sensors
    c. Fiber-optic magnetic anomaly sensors
2. Metamaterials (architected materials)
3. Sensors based on superconductor technology (bobbin material for superconductor coil/used to wind on fiber-optic cable)
4. Composite material systems

Applications for materials with an NCTE might be found in electro-optical sensor development programs within the U.S. Air Force Research Laboratory (AFRL) Sensors Directorate [2]. Applications may also be found in undersea sensor development programs within the U.S. Naval Research Laboratory Acoustics Division [3].

2.2 PUBLISHED RESEARCH: NCTE MATERIALS & SENSORS

DSIAC staff believed it would be instructive to consider NCTE materials without limiting the set to metals. Published research correlates material properties with the proposed applications: fiber-optic and photonic sensors, metamaterials (architected materials), sensors based on superconductor technology, and composite material systems. The research summarized next addresses NCTE materials, sensor types, and sensor mechanisms.

2.2.1 Fiber-Optic and Photonic Sensors

"Novel Signal Demodulation Technique to Estimate the Amount of Chirp in Fiber Bragg Gratings" by M. Kondiparthi [4]

Sensor type: fiber Bragg grating
Sensing application: strain (NCTE material balances strain due to thermal change)
NCTE material: negative NTE material
Abstract from research article [4]**:**

> A novel detection technique to estimate the amount of chirp in fiber Bragg gratings (FBGs) is proposed. This method is based on the fact that reflectivity at central wavelength of FBG reflection changes with strain/temperature gradient (linear chirp) applied to the same. Transfer matrix approach was used to vary different grating parameters (length, strength and apodization) to optimize variation of reflectivity with linear chirp. Analysis is done for different sets of 'FBG length-refractive index strength' combinations for which reflectivity vary linearly with linear chirp over a decent measurement range. This article acts as a guideline to choose appropriate grating parameters in designing sensing apparatus based on change in reflectivity at central wavelength of FBG reflection.

Key excerpt(s) from research article [4]**:**

> FBG is a systematic (periodic/aperiodic) modulation of refractive index in the core of a single mode optical fiber. FBGs were extensively used in measurements because of their multiplexing capability, immunity to EMI and non-corrosive nature. In FBG sensors, measurand (axial strain/temperature or any parameter which can affect the same)

variations causes a shift in the Bragg wavelength. As wavelength is an absolute parameter, independent of intensity losses and source intensity fluctuations, wavelength encoded operation provides unique advantages, but is difficult to analyze practically. Several systems exist to convert Bragg wavelength shifts into a proportional electrical (more convenient to process) signal. Most of these systems are targeted to measure Bragg wavelength shifts, which are sensitive to both strain and temperature applied to the FBG. Hence, with one single measurement of Bragg wavelength shift, it is impossible to discriminate between the effects of strain and temperature….

Configurations exists which can convert measurand variations into proportional strain/temperature gradient. ….. This is possible for neutral chirp (chirp which will not introduce any shift in Bragg wavelength) configurations10. Temperature effects can be compensated by attaching the FBG to a material10 with negative thermal expansion coefficient that strains the FBG in a way which compensates the effect of temperature on FBG.

"Optical Fibre Long-Period Grating Sensors: Characteristics and Applications" by S. W. James and R. P. Tatam [5]

Sensor type: fibre optic long-period gratings (LPGs)
Sensing application: temperature-insensitive strain sensors, high-resolution temperature sensors, axial strain sensors and torsion sensors, chemical concentration sensors, liquid level sensors, tunable spectral filter, tunable loss filter (temperature-insensitive filter or a species-specific chemical sensor), bend sensors
NCTE material: generic
Abstract from research article [5]**:**

Recent research on fibre optic long-period gratings (LPGs) is reviewed with emphasis placed upon the characteristics of LPGs that make them attractive for applications in sensing strain, temperature, bend radius and external index of refraction. The prospect of the development of multi-parameter sensors, capable of simultaneously monitoring a number of these measurands will be discussed.

Key excerpt from article [5]**:**

The sensitivity of LPGs to strain, temperature, bending and external refractive index, the ability to tune the sensitivity by virtue of fibre composition and LPG period, and the presence of features with the transmission spectrum that show differing sensitivities to the various measurands offer the prospect for the development of sensor elements capable of simultaneously and independently monitoring a number of measurands. This paper has discussed the properties of LPGs, techniques for their fabrication and the origin of their sensitivity to the various measurands. The means for optimizing the performance of the LPG for particular applications has been outlined, along with a review of the uses to which they have been put.

"A Novel Fiber Bragg Grating Temperature Compensated Strain Sensor" by D. Yanliang et al. [6]

Sensor type: fiber Bragg grating
Sensing application: strain
NCTE material: bimetal
Abstract from research article [6]**:**

This paper analyzed the strain-temperature cross sensitive characteristic of optical fiber Bragg grating (FBG) theoretically, designed and made a novel FBG strain sensor. It has a temperature-compensated function, and it improves the effect of being sensitive to strain. To a certain extent, this sensor overcame the traditional temperature-compensated methods easy to have a creep and aged phenomenon. The experimental results show that the sensor realized the temperature sensitivity reduces to 1/10 before the seal, and the strain sensitivity increases to 1.4pm/uε over the temperature range from -10 degrees C to 50 degrees C.

Key excerpt from article [6]:

We have demonstrated a compensated device which is relatively simple to construct, inexpensive to manufacture, easy to use, and yet reliable in operation. A specially designed innerstress mechanism included in this device can adjust the Bragg wavelength shift due to temperature. The experimental results indicated that the sensor temperature sensitivity was reduced to 1/10 of that of bare FBG, namely 1.2pm/°C; the strain sensitivity was increased to 1.4pm/με, which is very close to the theoretical value.

"Thermal Wavelength Stabilization of Fiber Bragg Gratings Using Bi-metal Structure" by S. C. Wang and H. H. Tsai [7]

Sensor type: fiber Bragg grating
Sensing application: strain

NCTE material: not cited
Abstract from research article [7]**:**

A stabilized laser is essential for optical fiber communication network. One of the passive technique for stabilization of central wavelength of laser is based on the application of fiber Bragg gratings. Due to the positive coefficient of thermal expansion of optical fiber, the Bragg gratings within the fiber written by excimer laser gives about 0.01nm/oC shift on the central wavelength respect to the ambient temperature which leads serious problem in the communication network. Since both the temperature and tension force are linearly proportional to the central wavelength of fiber Bragg gratings. A feasible approach to derive the wavelength stabilization is to decrease the tension force of fiber Bragg gratings respect to the increase of ambient temperature. In this paper, a bi-metal structure with similarly negative coefficient of thermal expansion is used to decrease the tension force while the environmental temperature increases. Results show that the theory provides a fundamental solution of the physical data of the temperature compensated fixture for near zero shift of central wavelength. The practical compensation of the bimetal structure is non-linear due to the thermal expansion of the arm of the fixture, while the compensation is linear respect to the ambient temperature by neglecting the thermal expansion of the arm. However, this package is feasible for mass production and can be used for athermalization of the fiber Bragg gratings in optical communication system.

"Tunable Fiber Bragg Grating Using Evanescent Field Coupling" by J. Jeong [8]

Sensor type: fiber Bragg grating
Sensing application: enhanced thermal tuning of an FBG device
NCTE material: Ti-Ni alloy
Abstract from research article [8]**:**

> FBGs have found many attractive applications in other parts of optical fiber communication systems, too, becoming an indispensable component. The spectral characteristics of the FBG filter are suitable for the DWDM add/drop filters and may compete with the thin film filters in the near future. The chromatic dispersion of an optical signal can be compensated using a chirped FBG, and the gain flattening of an erbium doped fiber amplifier (EDFA) can be realized by using a long period grating (LPG). Numerous applications in fiber and semiconductor lasers have been reported.7 The FBG also is widely used in sensor technology.

Key excerpt from article [8]:

Instead of using the thermal property of the fiber, H. Mavoori et al. used a combination of Ti-Ni alloy with a larger negative thermal expansion coefficient and Al alloy with a positive expansion coefficient and attached them on the fiber to enhance the thermal sensitivity of the FBG device.

"Controlling Thermal Expansion to Obtain Negative Expansivity Using Laminated Composites" by A. Kelly et al. [9]

Sensor type: fiber Bragg grating
Sensing application: generic (temperature, strain, pressure, tilt, displacement, acceleration, load, etc.)
NCTE material: laminated composite
Abstract from research article [9]**:**

It is confirmed, by considering a wide range of laminated composites containing a variety of fibres and matrices, that negative thermal expansion coefficients may be obtained. These are usually accompanied by a correspondingly large value of the in-plane axial Poissons ratio (PR). By making use of this large PR extremely negative values of expansivity may be obtained – much further negative than for any monolithic materials. The use of laminated composites also overcomes some of the previously reported limitations of a device to control thermal expansion when made with monolithic materials. The use of the device, as a platform to control the expansivity of an optical fibre containing a Bragg grating, is discussed in detail and it is shown that the required negative expansivity may easily be obtained with a number of composite systems.

2.2.2 Metamaterials (Architected Materials)

"Structurally Efficient Three-dimensional Metamaterials With Controllable Thermal Expansion" by H. Xu and D. Pasini [10]

Sensor type: flexible electronics, biomedical sensors, thermal actuators, and MEMS
NCTE material: octet lattice bi-materials (Al6061-Ti-6Al-4V)
Abstract from research article [10]**:**

The coefficient of thermal expansion (CTE) of architected materials, as opposed to that of conventional solids, can be tuned to zero by intentionally altering the geometry of their structural layout. Existing material architectures, however, achieve CTE tunability only with a sacrifice in structural efficiency, i.e., a drop in both their stiffness to mass ratio and strength to mass ratio. In this work, we elucidate how to resolve the trade-off between CTE tunability and structural efficiency and present a lightweight bi-material architecture that not only is stiffer and stronger than other 3D architected materials, but also has a highly tunable CTE. Via a combination of physical experiments on 3D fabricated prototypes and numeric simulations, we demonstrate how two distinct mechanisms of thermal expansion appearing in a tetrahedron, can be exploited in an Octet lattice to generate a large range of CTE values, including negative, zero, or positive, with no loss in structural efficiency. The novelty and simplicity of the proposed design as well as the ease in fabrication, make this bi-material architecture well-suited for a wide range of applications, including satellite antennas, space optical systems, precision instruments, thermal actuators, and MEMS.

2.2.3 Sensors Based on Superconductor Technology

"Effect of Thermal Cycles on Critical Current and AC Loss for Superconducting Coils Having Positive or Negative Thermal Expansion Bobbin" by T. Takao et al. [11]

Sensor type: superconducting coil
Sensing application: magnetic field anomalies
NCTE material: high-strength polyethylene fiber (Dyneema: DF) reinforced plastic
Abstract from research article [11]**:**

We investigated the effect of thermal cycles between room and liquid-nitrogen temperatures on the critical current (Ic) and AC loss of two superconducting coils: one with a bobbin that expands during cooling from room temperature to cryogenic temperature and one with a bobbin that contracts during the cooling. After 100 cycles, neither bobbin suffered degradation. The Ic of the contraction-bobbin coil did not decrease, and that of the expansion-bobbin coil decreased due to the repeated thermal strain. The expansion coil's AC loss was significantly smaller than the contraction coil's loss at the first cycle; however, it increased with the thermal cycles and eventually surpassed the contraction coil's loss because the Ic of the expansion coil decreased due to the thermal fatigue. These results indicate that a moderate expansion in the size of the bobbin effectively decreases AC loss and that excessive expansion reduces the Ic and increases the AC loss.

2.2.4 Composite Material Systems

"Reduced Thermal Stress in Composites via Negative Thermal Expansion Particulate Fillers" by W. Miller et al. [12]

Sensor type: magneto-electric sensors

NCTE material: NTE particles as composite fillers
Abstract from research article [12]**:**

The use of negative thermal expansivity (NTE) particles as composite fillers is relatively new and the particle–matrix interface is not well studied. This lack of understanding of the particle–matrix interface is further complicated as in many engineering applications, such as microchip packaging, the composite is constrained by its surroundings and is not free to expand upon heating; an important consideration that is often not taken into account. This paper presents a systematic theoretical study of the behavior at the particle–matrix interface under varying particle coefficient of thermal expansivity (CTE), Poisson's ratios (including negative Poisson's ratios), Young's moduli, boundary conditions and particle separation distances via finite element modelling and describes how to optimize composite formulation for problems of thermal mismatch through tailoring of particle–matrix interaction. The effects of reduced CTE are explored via models of electronic chip package assembly.

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