Embedding of Fiber Optic Sensors in Layered Manufacturing

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Abstract

Layered manufacturing enables integrating sensors during production of tooling or structural components. Sensors may be placed close to the points of interest prior to enclosure. Structures with embedded sensors are capable of monitoring parameters at critical locations not accessible to ordinary sensors. This work presents a methodology for embedding fiber optic sensors in metallic structures via Shape Deposition Manufacturing. Some of the main manufacturing issues are discussed. Embedded fiber optic sensors have been employed to measure temperature and strain. Proof-of-concept experiments on a non-contact fiber optic sensing system have been performed. By implementing the remote sensing system it is possible to measure temperature and strain of rotating components exposed to potentially hostile environments such as blades in gas turbine engines.

Introduction

Layered manufacturing processes provide capabilities not easily achieved with conventional manufacturing [1]. Examples include the ability to create complex three-dimensional shapes with internal cooling channels, to produce parts with continuously varying material properties and parts with embedded mechanical and electrical components. The possibilities also include embedding sensors and microprocessors to create "smart" products and embedding bearings, shafts and even bio-mimetic robotic mechanisms that have materials properties, tolerances, or finishes that would be difficult to obtain with traditional manufacturing process [2,3].

Building parts in incremental layers allows complete access to the internal geometry of components. It allows for the placement of sensors close to points of interest and for their subsequent enclosure. Such embedded sensors can add intelligence and enable real-time health monitoring at some critical locations not accessible to conventional sensors. In addition, embedded sensors can also be protected from damage by extraneous environmental effects. Embedded sensors can be used to obtain information on the performance and structural integrity of functional components in service, which is of prime importance to many industries. Examples include the manufacturing industry (molds, dies, drilling bits, etc.), the aerospace industry (components of jet engines), the oil industry (drilling equipment), the power industry (vessels and pipes), the automotive industry (components of motors), and construction industry (structural components in buildings). Past research has demonstrated the embedding of thin film sensors into metallic structures. In particular, embedded thin film strain gages have been characterized in a four-point bending test and the results show good accuracy and linearity when compared with theoretical models and commercially available strain gages [4].

Recently, fiber optic sensors and communication links were identified as promising candidates for integration into structural materials [5]. They offer immunity to electromagnetic interference, non-obtrusive embeddability, good resistance to hostile environments, and high bandwidth. One of the main problems for embedding thin film sensors into metallic structures is electrical insulation [4]. In contrast, fiber optic sensors do not need electrical insulation since they are not electrically conductive. Fiber optic sensors can provide sensing for structures operating at elevated temperature [6]. Furthermore, fiber optic sensors can be used to measure temperature and strain in a non-contact fashion [7]. This is especially significant when temperature and strain information need to be acquired from structures rotating in hostile environments, such as turbine blades. Traditionally, stationary flat or mildly curved plates are instrumented with surface mounted strain gauges and thermocouples [8,9]. For rotating blades, sensors are connected to the outside via slip rings. Naturally, such measurements yield low signal to noise ratios. In contrast, embedded fiber optic sensors can be employed for non-contact sensing of temperature and strain in rotating turbine blades.

In this work, a manufacturing method is described for embedding fiber optic sensors via layered manufacturing. The characterization of the embedded sensors is presented. Moreover, a remote fiber optic sensing system is discussed which allows measuring temperature and strain in rotating structural components.

Embedding Techniques for Fiber Optic Sensor

Fiber optic sensors consist of modified optical fibers. Optical fibers are circular dielectric waveguides, as shown in Fig. 1, and have a central core surrounded by a concentric cladding with slightly lower (by 1%) refractive index. Fibers are typically made of silica with index-modifying dopants such as GeO_2. A protective coating of cushioning material (such as acrylate) is used to reduce light loss due to microbending that occurs when fibers are pressed against rough surfaces and to provide protection to the fragile optical fiber core and cladding. The diameters of core and cladding for a single mode fiber are 9 μm and 125 μm respectively.

The challenge for the embedding originates from the fact that the fiber needs to be embedded in high melting temperature metal structures. The fiber optic sensors will need to be protected during the high-temperature deposition steps. In particular, a protective layer is necessary to overcome temperature and stress experienced by the optical fibers during the formation of embedding layer. Apparently, the soft and low temperature coating of the optical fiber must be replaced by a metallic coating. Electroplating of Nickel is selected. Nickel has high thermal conductivity, and bonds well to the subsequently deposited steel layer.

The embedding sequence developed at the Rapid Prototyping Laboratory of Stanford University involve cleaning of fiber and substrate, sputtering thin film conductive layer, electroplating of Ni, and high temperature embedding. The process sequence is shown in Fig. 2.

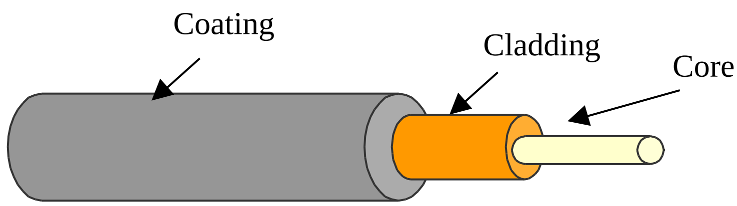

Fig.1 Optical fiber

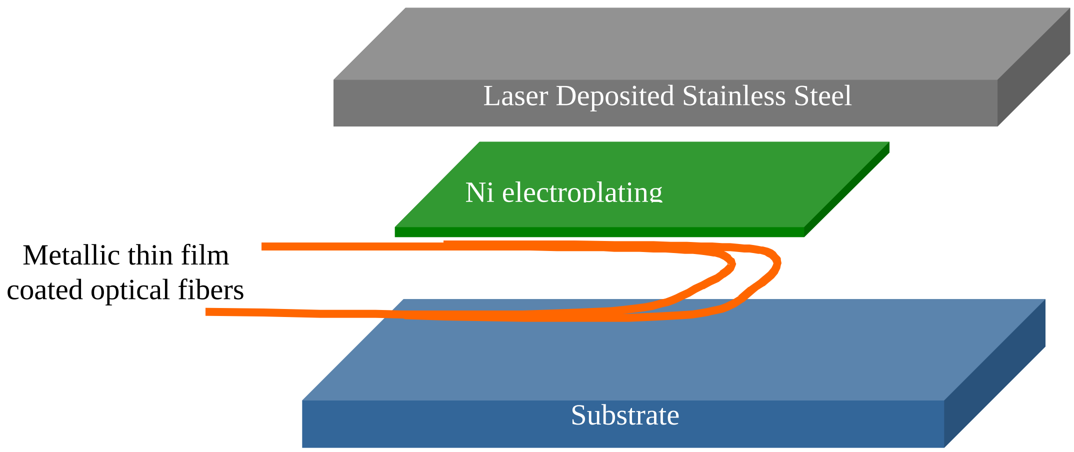

Fig.2. Explosive view of embedding sequence

Cleaning

The substrates have to be cleaned before electroplating. To remove salts, oils and grease the substrates are rinsed in borothene, acetone and isopropanol. Then the substrates are blown dry with dry nitrogen, rinsed with de-ionized water and dried again. The above steps are repeated once more and then the substrates are immersed in a 1:15 solution of micro-detergent in de-ionized water and are placed in an ultrasonic bath for 5 minutes. Finally the substrates are rinsed with copious amounts of de-ionized water and blown dry with dry nitrogen.

The cleaning process of optical fibers is much simpler since optical fibers come with coatings. However, the polymer coatings need to be stripped before the optical fibers are embedded into metallic structures. Normally, a mechanical stripper is the standard tool for this purpose. However, the fiber optic sensors come in without coating in the sensing element. The interface between the cladding of sensing area and the neighboring polymer coating, as shown in Fig. 1, creates a stiffness mismatch and the fragile sensing element (without polymer coating) is easy to break during the mechanical stripping. More over, the mechanical stripping sometimes leaves residues of the polymer coating on the surface of the cladding. The residues may induce microbending and debonding during the later high temperature embedding. Thus, a chemical stripping process is applied. The optical fibers are immersed in a bath of acetone for about 10 minutes. The polymer coatings then detach the cladding of the fiber. The process yields no stress and no residues while the sensing elements remain undamaged.

Sputtering

The thin film deposition system consists of a stainless steel cylindrical chamber of 62l capacity (diameter: 46 cm, height: 38 cm), with two K.J. Lesker 1-KW magnetron guns. The bare optical fiber is sputter coated with a thin titanium film (< 1μm) to enhance adhesion. Then a thin nickel film (< 0.2 μm) is sputter coated over the thin titanium film. A short period (< 10min.) of Ni thin film sputtering is preferred since the Ni target becomes hotter and hotter during the sputtering. The resulting hotter plasma in the chamber may induce microcracks in the fiber optic sensor due to temperature gradients.

Electroplating

The deposition of the nickel layer on the substrate is performed in two steps. First the "seed" layer is grown in a nickel "strike" bath. Prior to the "seed" layer deposition the substrate is subjected to electropolishing by the application of a reverse voltage (substrate connected to the anode) for 2 minutes. Then the voltage is reinstated to its forward direction and the deposition commenced. Then the optical fiber can be placed on the substrate in a designated path (straight or curved), which can be created manually or patterned by machining or by LIGA/MEMS techniques. The other areas of the substrate are covered by insulating layers, which can be formed by photoresist, resin, or kapton tape. The substrate is then transferred immediately to the electroplating bath for the growth of the nickel layer up to about 0.5~1 mm thick. To ensure low residual stresses from the electroplating process, Barrett SN solution (Nickel sulfamate) plating bath is used. The temperature of the plating bath is controlled at 49°C. A DC power supply is applied to control the current density. At the first hour of plating, the current density is set at 0.215 mA/mm^2. Afterwards, the current density is raised as 0.646 mA/mm^2. At the end of the deposition sequence, the substrate is retracted from the solution and all protective insulating layers (photoresist, resin, kapton tape) are removed. Finally, the substrate is rinsed in distilled water and blown dry.

Embedding

The optical fiber can then be electroplated into thicker nickel layer or embedded to the other metallic structures by high temperature processing (casting, welding, arc spraying etc). In the Rapid Prototyping Laboratory, a 2400W, CW Nd:YAG laser is used to fuse metal powders. The powders are pre-placed on the surface of the nickel layer from a single powder feed nozzle. Laser power is controlled automatically and the deposition apparatus is moved across the surface of the substrate using a four degree-of-freedom robotic manipulator. By using this system, the composition of the deposit at any point on the surface can be accurately controlled.

Process and Manufacturing Issues

There are more issues involved. Sensors need to be placed at the points of interest inside the metallic components. We will focus our discussion on Shape Deposition Manufacturing (SDM) which was reported elsewhere [1]. The manufacturing cycle for embedding fiber optic sensors into functional parts can be depicted in Fig. 3.

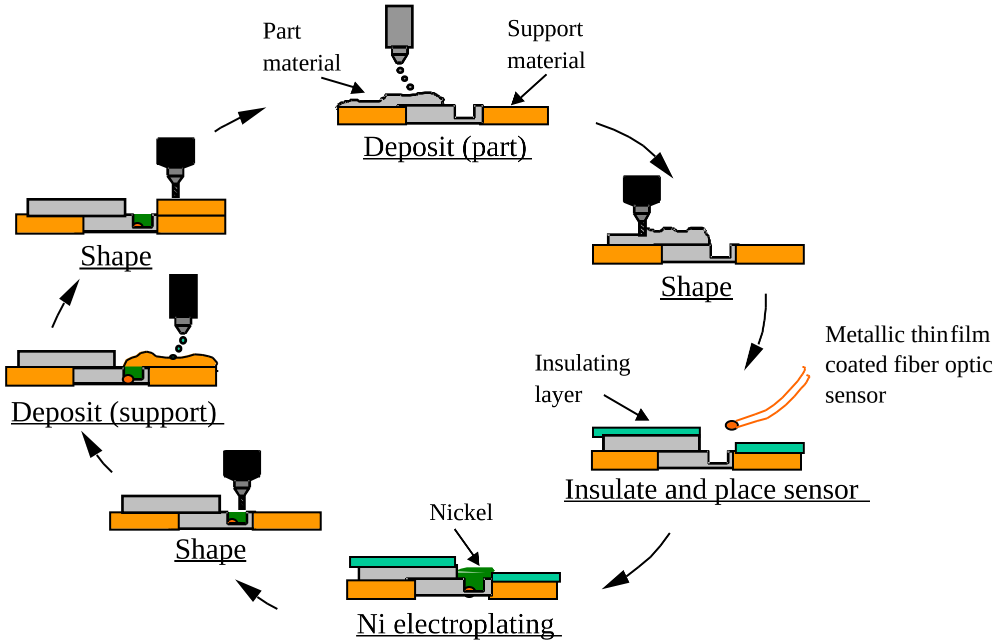

Fig.3. Shape Deposition Manufacturing cycle for embedding fiber optic sensors

The main issues are the bond quality between the nickel layer and the substrate, thermal stress due to a large temperature gradient during layered deposition, and fragile ingress and outgress points of optical fibers from the metal part. During the manufacturing cycle, two types of defects, delamination and crack, will damage the optical sensors and the strength of the structure. The delamination or micro-crack can be caused by inadequate cleaning of optical fibers and substrates. Fig. 4a shows a crack in the boundary between an optical fiber and the electroplated nickel while Fig. 4b display a delamination due to the inadequate cleaning of the substrate. Delamination or cracking may also originate during or after high temperature embedding. Laser cladding, which is similar to welding process, is used in this study. Cladding parameters for nickel are similar to those used to stainless steel, except the molten nickel weld pool is more difficult to control. The adequate mixing of the molten nickel and stainless steel power is crucial for good bonding. Fig. 4c shows a crack at the interface between laser-deposited stainless steel and electroplated nickel. In Fig. 4d, one can observe delamination, cracks and voids due to the inadequate cleaning, lack of molten metals mixing, and thermal stress.

Several processing steps have been investigated to eliminate defects. By optimizing the cleaning process and laser cladding parameters, the quality of embedding can be improved significantly, as shown in Fig. 5. The bonding strength between substrate and electroplated nickel can be enhanced by sand blasting the part before electroplating.

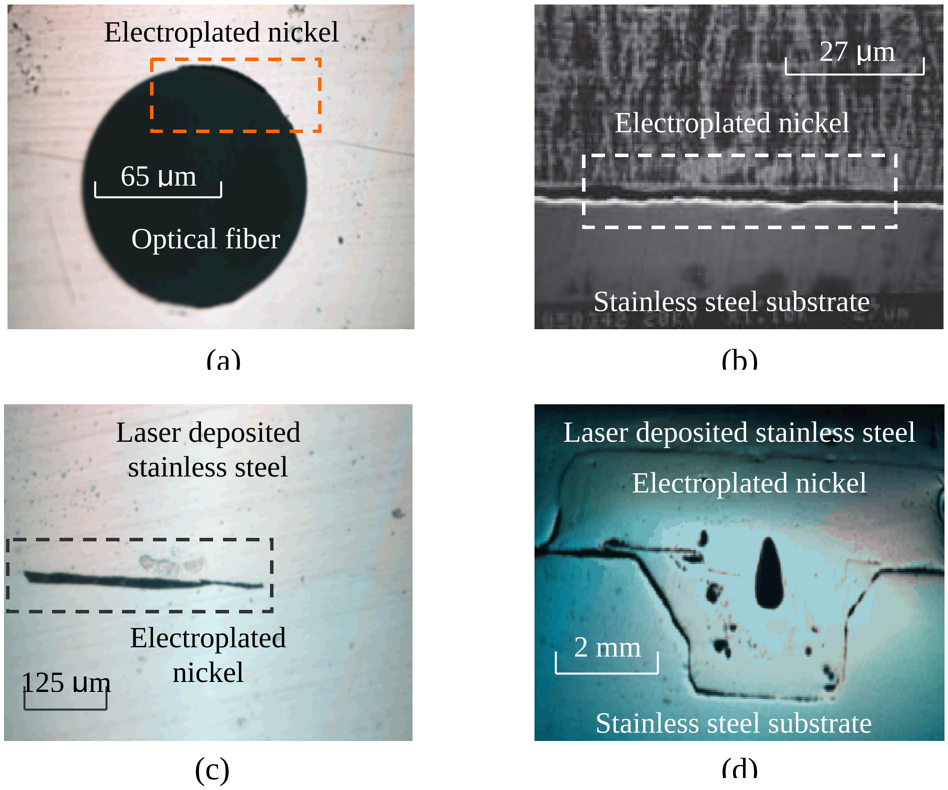

Fig.4. Defects during manufacturing cycle

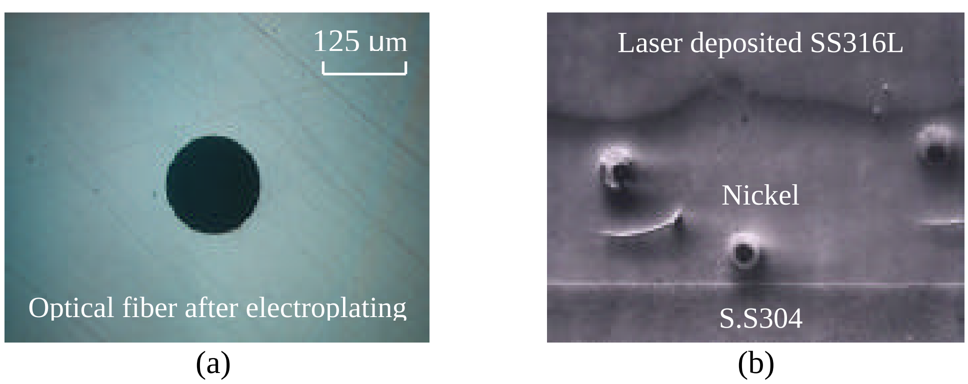

Fig.5. Embedded Optical fiber with good bonding

Since SDM is an additive and subtractive process, the ingress and outgress points of the fiber optic sensors from the metallic structure need extra protection. In particular, the optical fibers are very fragile during the "shape" process because chips from machining processes can easily cut off exposed optical fibers. One way to prevent this problem is to put nickel coating on the extra length, normally above 10 mm, of optical fibers outside the ingress and outgress points and to protect the extra fiber by using a polyethylene furcation tube with 1.2 mm diameter.

Another way is to completely eliminate the problem by cutting away all extra fiber leads outside the parts. This requires a non-contact sensing system to launch light into the optical fiber and to receive the light signal. The new technique will be discussed later in this paper.

Characterization of Embedded Sensors

Since the sensor is coated with a nickel layer before embedded in stainless steel layers, it is necessary to study the characterization of the electroplated nickel as well as the sensor behavior under thermal and strain loads.

The microstructure of electroplated nickel is so fine that Scanning Electron Microscope (SEM) is not enough to reveal its grain size. By using Transmission Electron Microscope (TEM), the microstructure of electroplated nickel is shown in Fig. 6. The grain size is about 150 nm. With such a fine grain, it is expected that the mechanical properties of nickel will be significantly improved. In a tensile test, the yield strength, tensile strength, and strain to failure are found to be 928.72 MPa, 946.65 MPa, and 4.6% respectively. Even without the high temperature embedding of stainless steel, the strong mechanical strength plus the corrosion resistance of electroplated nickel is suitable to produce embedded fiber optic sensors for special purposes, such as oil well and deep sea temperature/pressure monitoring.

However, there is a thermal effect to the fine nickel microstructures during the laser cladding process. Actually the grain sizes become much larger than the electroplated ones. Obviously, the electroplated nickel recrystallizes during and after the laser cladding because the laser melts part of the nickel layer to mix it with molten stainless steel powder. Fig. 7 shows that the grain size of the nickel is decreasing from about 200 μm near the interface, between the laser deposited stainless steel (at right) and the nickel (at left), to about 10 um at a distance of 3 mm. The revealed microstructure changes are believed to result in lower mechanical strength but higher strain to failure.

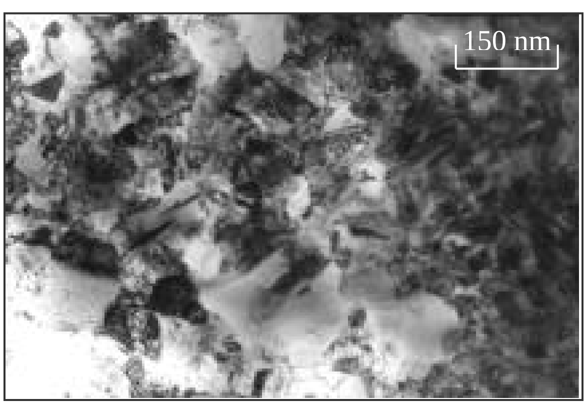

Fig.6. Microstructure of electroplated Ni (TEM)

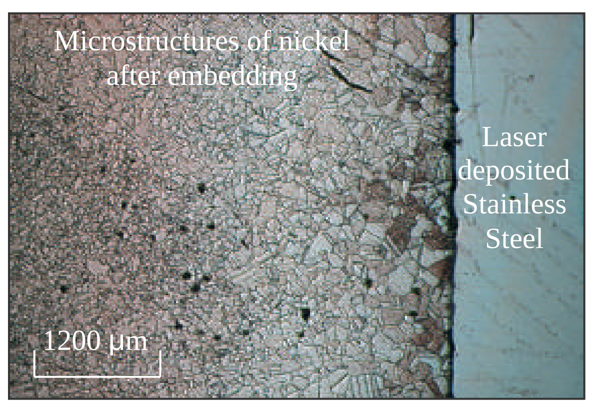

Fig.7. Microstructure of electroplated Ni after embedding

Sensor behavior

Fiber optic sensors, such as Michelson, Fabry-Perot, and Bragg Grating, have been embedded in nickel and stainless steel structures. They provide higher sensitivity, good accuracy, and high temperature capacity. For Michelson and Fabry-Perot sensors the potential operating temperature can be up to 1100 °C (limited by the silica fiber itself) while for Fiber Bragg Gratings operation up to about 500 °C (limited by the Bragg grating) is possible [7]. In this article, Fiber Bragg Grating (FBG) sensor is tol be discussed.

FBG is compact, simple and can be demodulated in a wavelength-coding manner. When the FBG is expanded or compressed, it changes the grating spectral response. The Bragg condition is given by

$$\lambda_0 = 2\, d\, n_{core}$$

where λ_0 is Bragg wavelength, d is the distance of pitches of the grating, and n_{core} is the refractive index of the core. The wavelength change due to temperature and strain is given by

$$\Delta\lambda/\lambda_0 = (\alpha+\zeta)\Delta T + (1-p_e)\varepsilon$$

where α is the coefficient of thermal expansion (CTE), ζ is the photothermal coefficient, and p_e is the photoelastic coefficient. By measuring the wavelength, temperature/strain can be determined. Fig. 8 presents the experimental results. The temperature sensitivity of the embedded FBG is almost two times higher than that of bare FBG. The strain dependence of the FBG matches the theoretical results very well [7].

Rotating Parts with Embedded Sensors for Remote Sensing

Since light is used for the fiber optic sensors, it is possible to develop a remote sensing system to monitor the temperature and strain in rotating objects, such as turbine blades. The system is sketched in Fig. 9. After embedding the fiber optic sensors into a rotating part, a high speed wavelength tunable laser GCSR laser diode [10] can be used to launch light into the embedded sensor and the output signal, modulated by the temperature/strain, can be collected by a photo-detector or an optical spectrum analyzer (OSA). Erbium-doped Fiber Amplifier (EDFA) is used to amplify the optical signal since light loss is a main concern due to the small size of optical fibers. Under a load (temperature or strain), the fiber Bragg grating reflects only single wavelength and all other lights with different wavelengths will go through to the photo-detector or OSA. Thus, at that single wavelength, the received light intensity will drop to almost zero. Thus, the Bragg wavelength under the load can be determined. The load can then be determined by the Bragg wavelength shift.

To prove the concept of the system, a part with embedded FBGs is manufactured via SDM, as shown in Fig. 10. By applying thermal/strain loads, the wavelength shifts in the FBGs are monitored. Experimental results are shown in Fig. 11 with pictures scanned from the OSA. It clearly demonstrates the Bragg wavelength shifts after loads are applied. The result in light power domain (from photo-detector and oscilloscope) is shown in Fig. 12. The voltage is negative so that a pulse signal is shown instead of the proposed signal from the sampling scope in Fig. 9. All the results suggest the remote sensing system is feasible to monitor the temperature and strain variations for rotating turbine blades, if embedded with fiber optical sensors.

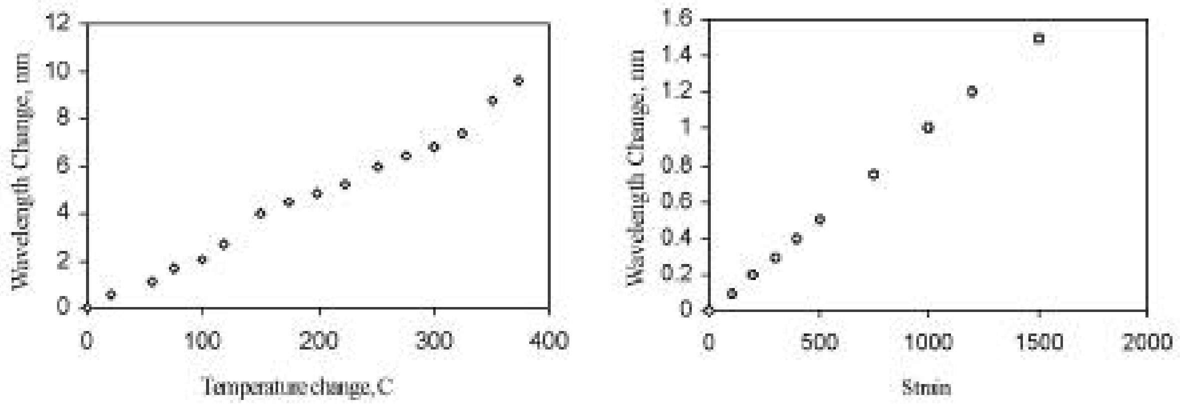

Fig.8. Experimental results for embedded FBG

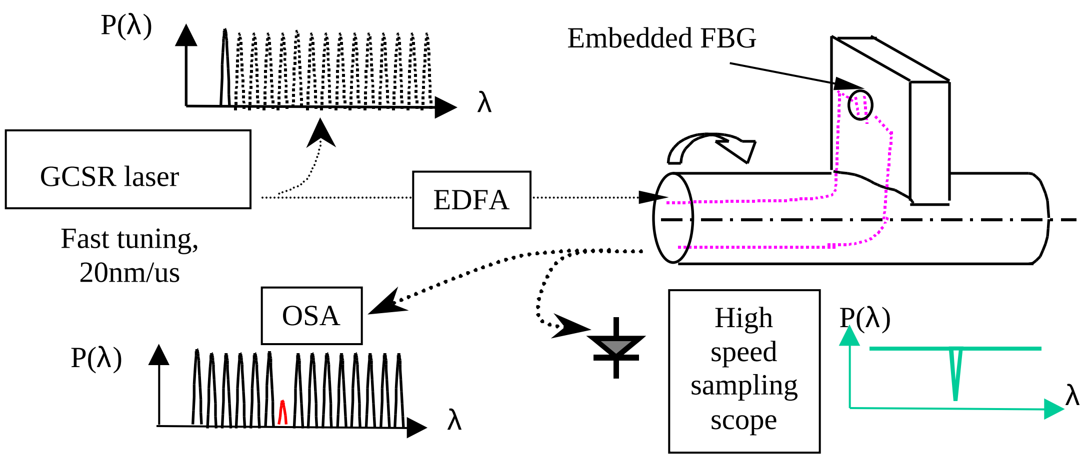

Fig.9. Remote sensing system for rotating parts with embedded fiber optical sensors

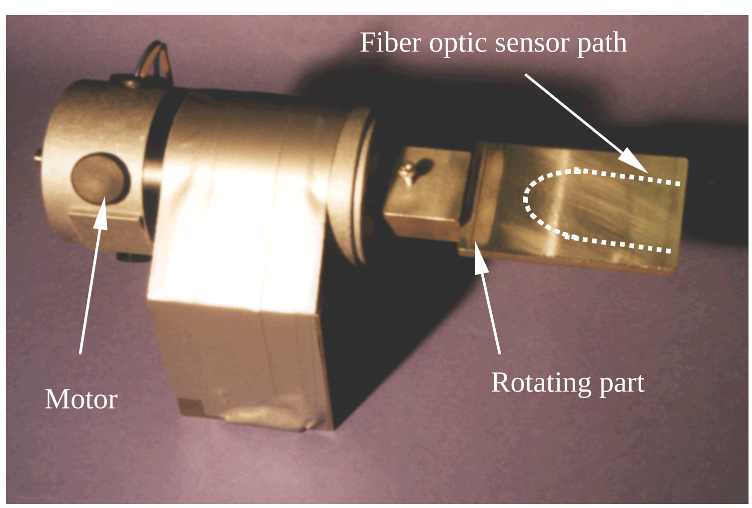

Fig.10. Rotating part with embedded fiber optic sensor

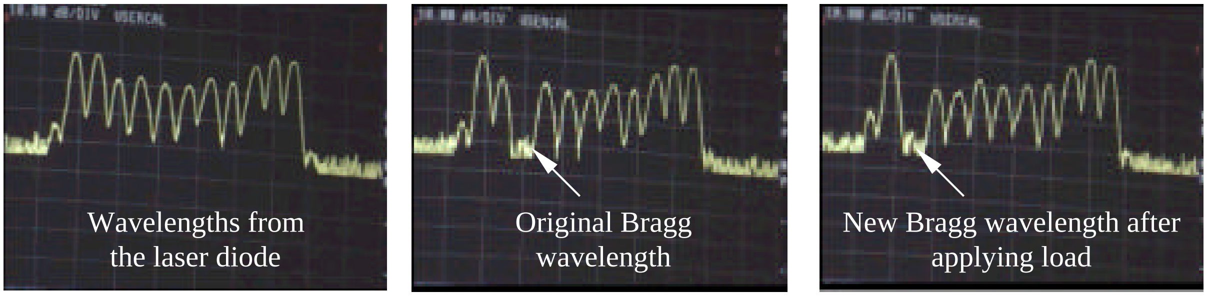

Fig. 11. Bragg wavelength shifts on OSA for the rotating part

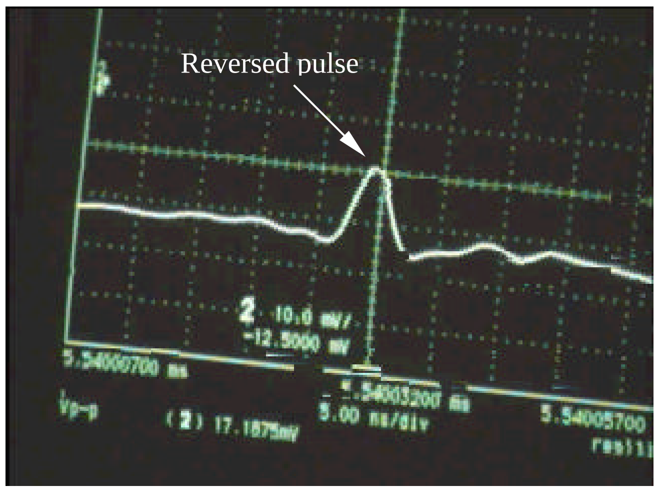

Fig.12. Pulse signal in oscilloscope

Conclusion

Layered manufacturing enables integrating sensors during production of tooling and structural components. Sensors may be placed close to points of interest prior to enclosure. This paper presents a method for embedding fiber optic sensors in metallic structures via Shape Deposition Manufacturing. Manufacturing issues, such as integrity of the structures with optical fiber sensors, are discussed. Embedded fiber optic sensors are characterized, showing linearity, high sensitivity, and accuracy. Proof-of-concept experiments on a non-contact fiber optic sensing system were proposed and tested. Remote sensing is feasible to measure temperature and strain of rotating components exposed to hostile environments such as blades in gas turbine engines.

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