# Process for Mounting and Packaging of Fiber Bragg Grating Strain Sensors for use in Harsh Environment Applications

by

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## ABSTRACT

In this paper, we report the development of a new bonding agent and method for the surface mounting of optical fiber Bragg grating strain and temperature sensors for use in harsh environments. The compound is based on a combination of ceramic fillers with an epoxy binder that is applied with a brush technique. Samples of optical fiber Bragg gratings were successfully encapsulated and mounted on metal shims. The packaged sensors were tested for strain (+/- 1000με) and temperature (-20 to +120 °C) response. The encapsulated sensors display a linear response with an increase in the temperature sensitivity of the FBG, with a factor of 24.37pm/°C, and a strain gauge factor of 1.25pm/με.

**Keywords:** Optical fiber, Bragg grating, fiber sensor, harsh environment, fiber packaging.

## 1. INTRODUCTION

Over the last few years, optical fiber sensors have seen an increased acceptance as well as a widespread use for structural sensing and monitoring applications in civil engineering, aerospace, marine, oil & gas, composites and smart structures[1]. Optical fiber sensor operation and instrumentation have become well understood and developed [2]. However, one of the areas in need of further development and commercial maturity is that of sensor packaging and installation technique.

In this regard, there is a need to develop appropriate protective coatings and housings for fiber sensors; investigate the fundamental transfer of strains, stresses, pressure and temperature from the host specimen or matrix to the sensing fiber and the associated materials inter-play; as well as the development of field installation processes and deployment techniques suitable for the various application areas and expected environmental conditions. This is particularly attractive for harsh environment areas where conventional foil strain gauges cannot operate.

There are a variety of applications within the automotive, aerospace, electrical power, industrial process as well as the oil & gas industries that call for strain sensors capable of measuring static and dynamic stresses under harsh environments and at elevated temperatures in the 200°C – 800°C range. Some examples of typical applications are strain monitoring in manifolds for gas and diesel engines; strains in jet turbine blades; power plant pipeline and furnace stress measurement; stresses and crack monitoring on airplane wings, rocket boosters and fuselages; etc.

At these elevated temperatures, conventional foil strain gauges cannot operate. As an alternative, engineers have resorted to the use of free-filament and weldable resistive gauges [3]. Although, in many instances, it is possible to use and install said strain gauges using Rokide flame spray or ceramic cements combined with spot welding of shim substrates, the devices themselves present performance limitations due to thermal errors, large zero drifts, non repeatable readings, difficult signal conditioning, and susceptibility to moisture and EMI interference.

Optical fiber sensors, in contrast, offer the possibility to perform strain and temperature measurements under harsh conditions in the presence of electrical noise, EMI interference and mechanical vibrations. Intrinsically, silica-based glass fibers are capable of operating up to 800°C—granted their protective polymeric coatings are removed, or high temperature ones are used. For higher temperatures, sapphire fibers can be used, allowing their operation at temperatures as high as 1500 °C.

With the proper annealing treatment, FBGs can be used to monitor strains, long-term, without fear of decay of the optical reflectivity, unwanted spectral shifts or erasure of the photosentive effect at temperatures <400 °C [4]. For higher operating temperatures (<1000 C), it is possible to use so-called chemical composition gratings (CCGs) [5] where the refractive index modulation that defines the Bragg periodic structure is caused by a change in the chemical composition—rather than electronic defects and strained bonds—and hence, the thermal stability of the FBG will depend on a much higher activation energy and consequently more stable gratings at elevated temperatures.

In the sections to follow, we describe in more detail an encapsulating protective compound and packaging process for optical fiber sensors and FBGs that allows their use in harsh environment applications. To validate the efficacy of the encapsulant and the proper strain/stress transfer from the host to substrate and to the fiber sensor, we performed tensile tests and environmental temperature cycling tests.

## 2. FBG STRAIN SENSOR MOUNTING AND PACKAGING

The packaging materials and processes used in this work are, to a large extent, based on many years of experience with the handling and application of ceramic cements and Rokide flame techniques for the installation of free-filament resistive strain gauges in aerospace and other harsh environment applications.

Three distinct application methods with differing adhesive compounds were manufactured. Two of the three compounds were evaluated for their efficacy in bonding fibers to a metal shim substrate. The metal shim in all applications is a Hastalloy X super-alloy, which gives excellent strain transfer characterisitics, excellent oxidation resistance with temperature and moisture, as well as 10.8 ppm/degree Celsius thermal expansion; which matches structural steels. One process used a ceramic cement compound, while the other used a fiberglass pad with a different polymeric bonding compound.

A total of 6 FBG strain sensors were prepared and mounted. The fiber gratings had polyimide coatings and were inscribed using a 334nm UV laser exposure with a phase mask, using hydrogen-loaded fibers. The peak reflectivity values were typically >90% and located in the C-band around 1550nm. The physical grating length was approximately 1cm in all samples.

Two sensors were mounted using a high content silica-filled ceramic epoxy. This particular epoxy was chosen due to its water resistant characteristics and for its elevated temperature range for operation. This epoxy has been used for applications in the 350 degree C range. Since most polymeric adhesives creep with moisture and temperature, tests were performed to verify the amount these effects were seen in the strain measuring system.

Two additional sensor samples were made with ceramic cement (Fig. 2.2). The cement used is HPI 701 cement. It was chosen because of its high silica content which was felt would make the cement match the thermal expansion of the actual fiber itself. The cement is an older composition used for many years for general high temperature strain gage applications. The electrical characteristics are not as good as newer cements, but that is not a concern with fiber optic based sensors. This cement is usable to extremely high temperature applications in the 700 degree C range. It also does not have the shrinkage or creep issues associated with epoxy-based cements.

The final two sensors were manufactured using a pure aluminum oxide sprayed coating (see Fig. 2.3). Again, this technique has been used for high temperature strain gage applications for many years and does exhibit any creep or shrinkage issues like polymeric based adhesives. This type of application has the potential to be usable to over 1200 degree C operation.

Figure 2.1. Aspect of mounted FBG using silica-filled epoxy compound and glass onto a metal shim.

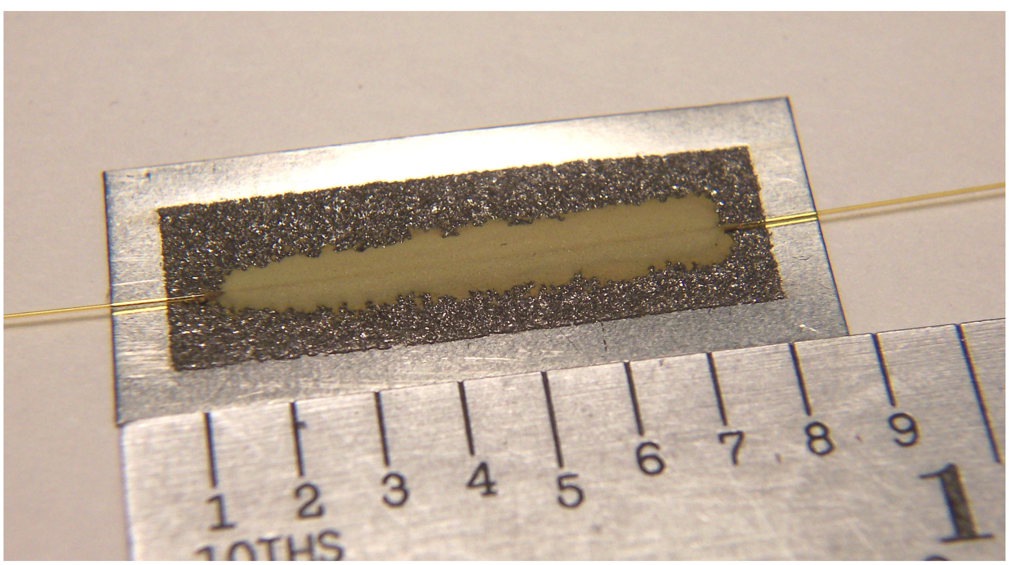


Figure 2.2: Aspect of mounted FBG using ceramic cement onto a metal shim.

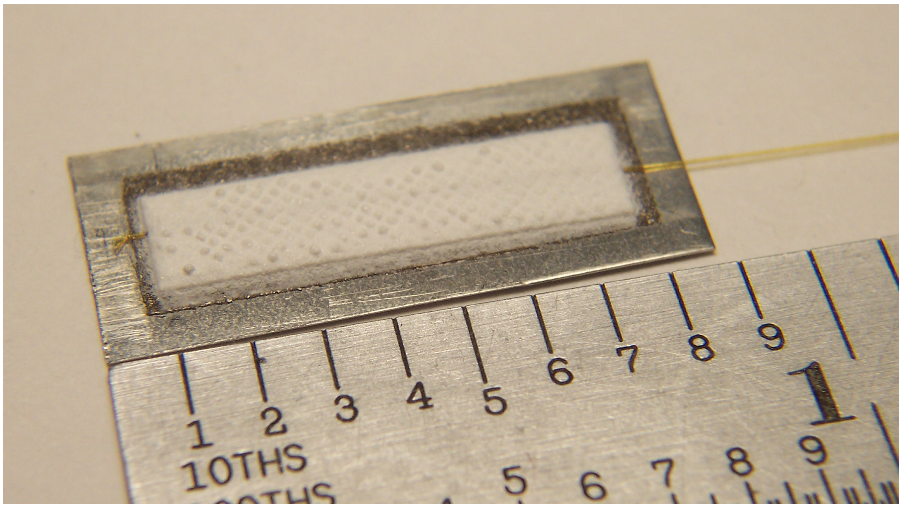


Figure 2.3: Aspect of mounted FBG using sprayed Alumina onto a metal shim.

## 3. STRAIN AND TEMPERATURE RESPONSE TESTING

Once pre-mounted onto a metal shim substrate—using each of the two described bonding processes—the FBG strain sensor samples were subsequently attached to a steel beam using a portable spot welder machine for strain gauge applications. As depicted in Fig. 3.1 below, it can be appreciated the multiple contacts points made by the welding tip on the shim. The metal shim remained in good contact and flat with respect to the metal beam.

Although it was not implemented in this work, it is recommended to strain relief the entry point of the optical fiber at the shim/cement boundary. This could be accomplished using Teflon tubing or any other suitable furcation tubing made of a compliant material to avoid damaging the fiber, which can withstand the operating temperature range. It is also recommended to secure the free end of the fiber with tape to avoid any unwanted movement or twisting, which might result in the breaking of the fiber at the cement bond interface point.

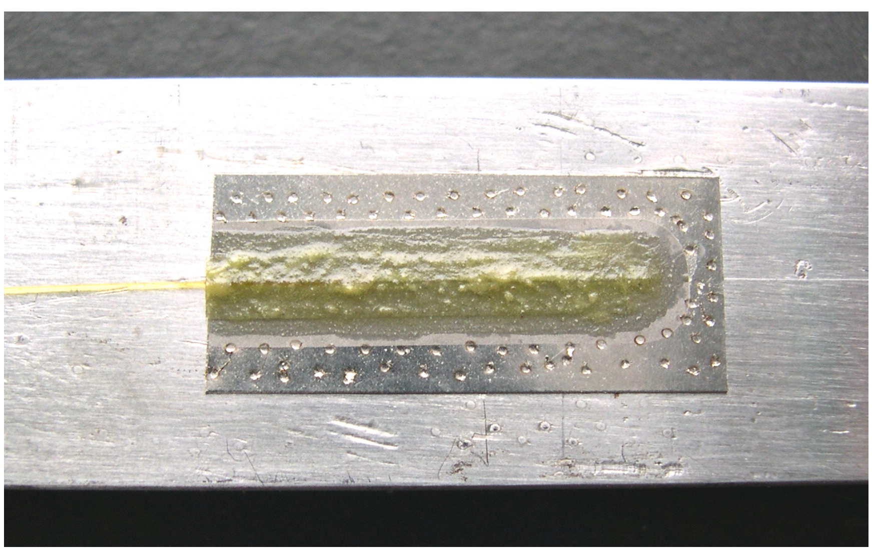

Figure 3.1: Aspect of pre-packaged FBG strain sensor spot-welded onto a metal beam.

**3.1 Strain Testing**

Prior to the actual mounting of the FBGs onto the shim substrates, scans of the un-strained grating reflectivity were taken. This helped determine the induced residual stress and any possible induced or distortion effects resulting from the encapsulating and mounting process. Fig. 3.2 is a superposition of different spectral reflectivity traces for sample HPI-A. This sample was mounted using the highly silica filled epoxy manufactured by Epoxylite Corporation.

It can clearly be appreciated that the bonding compound introduces compressive stress in the bare fiber grating that result in a residual curing strain equivalent to a peak wavelength shift of -2.29nm. This is equivalent to a residual compressive strain of approximately -1900με. The bonding process also broadens slightly the grating—probably due to a localized non-uniform strain along the entire grating length—however, there is no appreciable drop in the magnitude of the optical reflectivity, indicating there is no loss induced or damage being inflected on the fiber itself.

The mounting of the pre-packaged FBG onto the test beam—using spot welding—produces tensile stress from the stretching of the metal shim onto the support substrate. This results in a spectral shift of +0.762nm, which is approximately equivalent to +635με of tensile residual strain. The welding of the shim also introduce non-uniform strain along the mounted grating, giving rise to a more pronounce chirping and broadening of the FBG reflectivity. We are investigating was to reduce the amount of this residual stress, by altering the composition of the ceramic cement. Upon application of tensile or compressive loads on the support beam, the FBG deformed proportionally and linearly with the applied stress. For instance, the net spectral shift under a 1000ue load can be readily seen in Fig. 3.2. It can be appreciated that no reflectivity loss or additional distortion was introduced to the spectral envelope of the FBG.

The strain response of the sensor was tested for linearity, hysterisis, and gauge factor sensitivity by applying compressive and tensile loads at a constant rate using a universal testing machine. The samples underwent several cycles of load to see if there was any induced residual effect and zero-strain shifts. From Fig. 3.3, it can be appreciated that the packaged FBG response is repeatable and linear, with an equivalent strain gauge factor of 1.25pm/με in the range of –1000 to + 1000με and at room temperature.

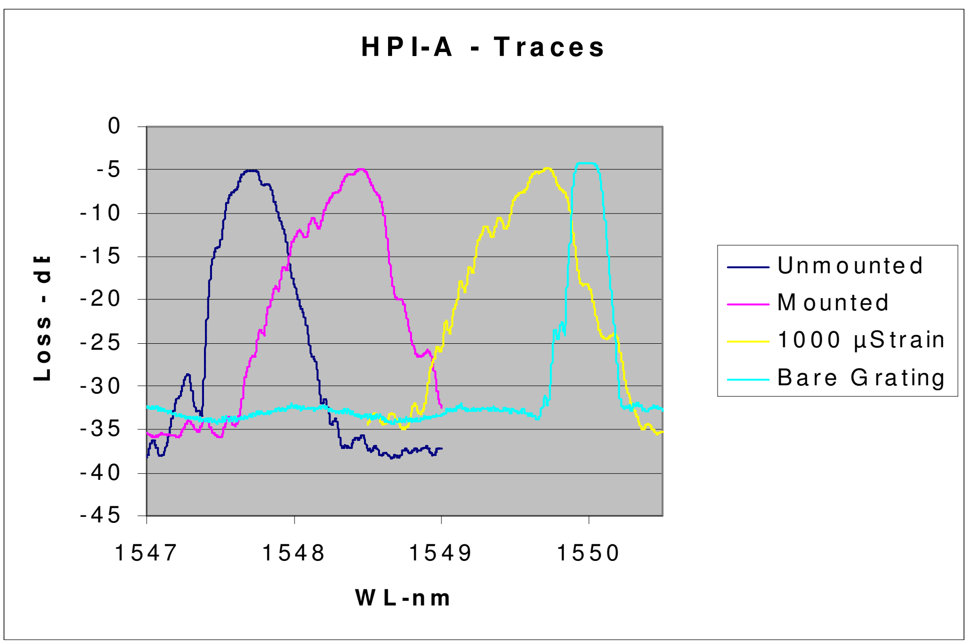


Figure 3.2: Spectral reflectivity for FBG sample HPI-A at different stages of packaging and testing.

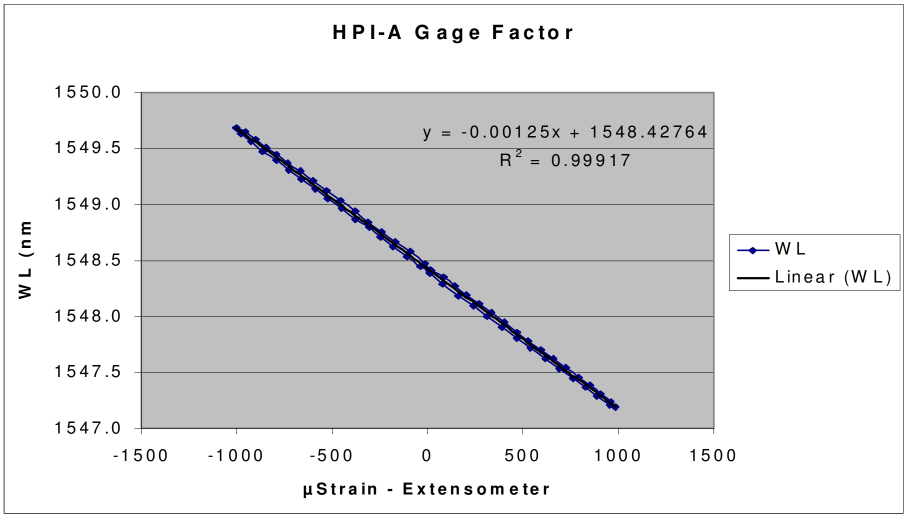


Figure 3.3: Strain response for FBG sample HPI-A.

## 3.2 Temperature Testing

The temperature response of the mounted FBG sensors was investigated by measuring the spectral shift as a function of applied temperature. The FBG sample mounted on the metal shim was placed inside a temperature-controlled chamber. The temperature was varied from –20 C to +120 C. Several temperature cycles were performed to detect any possible non-linearities, hysterisis or zero-temperature shifts. As seen from Fig. 3.4, the packaged sensor's response is repeatable and linear with applied temperature. The thermal coefficient of sensitivity was calculated to be 24.37pm/C. This is practically a factor of 2 greater than the intrinsic bare FBG temperature sensitivity. This is not surprising but rather the result of the sensitivity enhancement brought by the larger coefficient of expansion of the bonding compound. Depending on its formulation and additives, it will be possible to tailor—to some extent—the temperature sensitivity of the packaged FBG strain sensor. We will be conducting more experiments in this area.

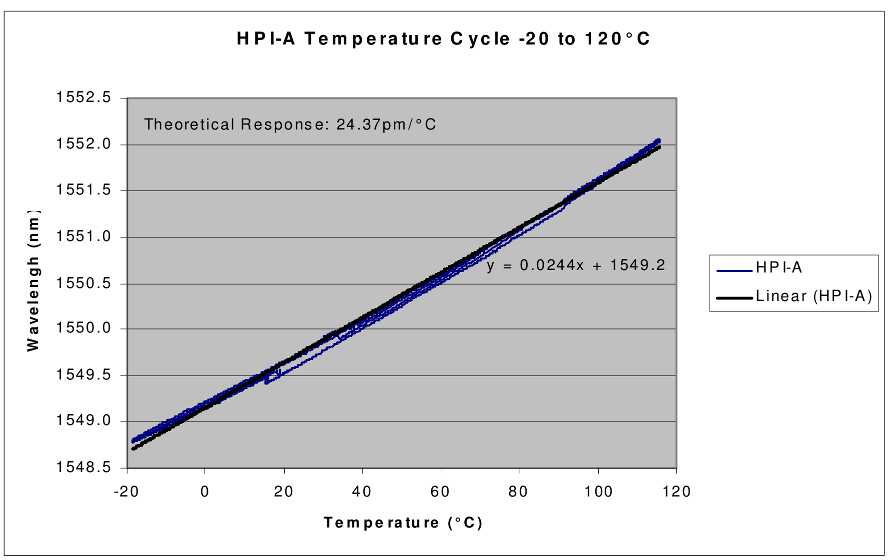


Figure 3.4: Temperature response for FBG sample HPI-A

### 3.3 Humidity Testing

To verify the hermeticity of the bonding compound, as well as to determine the resistance of the package strain sensor to harsh environments, a temperature/humidity soak test was performed at 75C/75% RH.

The FBG strain sensor was mounted on a constant stress beam using M-Bond AE-10 epoxy and cured according to the instructions. This beam is designed so that the surface strain developed during bending is very uniform along the length of the beam and remains nearly constant with temperature. For reference, a conventional foil strain gage was mounted on the opposite side of the beam directly under the test gage. The performance of the foil gage was previously verified using an Epsilon extensiometer. The entire beam assembly was placed in an environmental chamber allowing temperature and humidity control. The beam was then deflected and locked into position, resulting in 1000με tension on the surface of the beam at the gage location. While monitoring temperature, humidity, and strain as recorded by foil gage and FBG sensor, the chamber temperature was increased to 75˚C and allowed to stabilize. Humidity was then increased to 75% and held constant. Strain was as measured by the FBG sensor and foil gage and recorded as a function of time. The spectral shift as a function of time is shown below in figure 3.5. The duration of the test plotted in Figure 3.5 is 72 hours. The FBG sensor shows a downward drift in strain over time when subjected to high humidity. Approximately 156pm or 130με of relaxation occurred during the 72-hour test period.

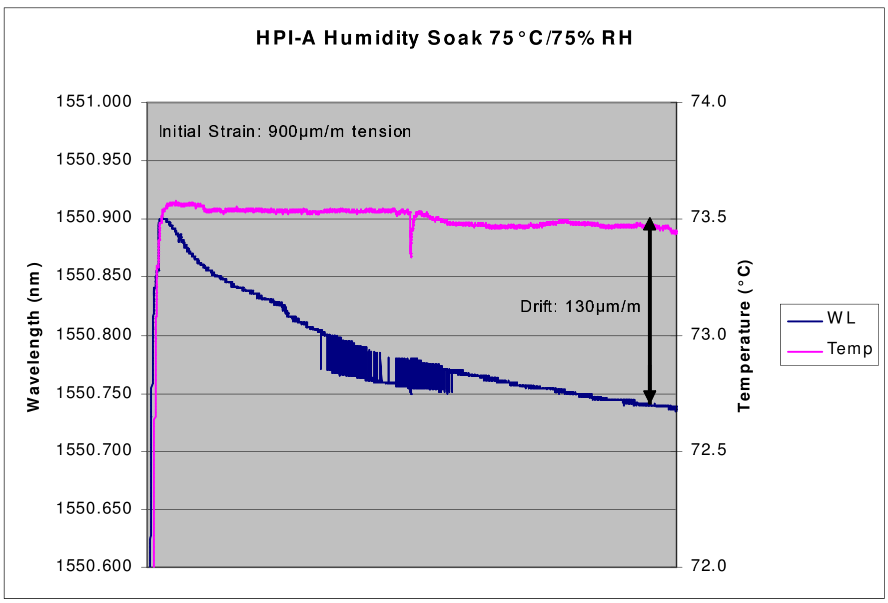


Figure 3.5: Humidity response for FBG sample HPI-A.

## 4. CONCLUSIONS

A new bonding agent and method for the surface mounting of optical fiber Bragg grating strain and temperature sensors for use in harsh environments was developed and described. Two different bonding compounds were tested for their efficacy of bonding strength, strain transfer and environmental protection. Of the two agents used, the ceramic cement turned out to be the preferred material. Optical fiber Bragg gratings were mounted onto metal shims as support substrates. The mounted sensors were tested for strain and temperature response. The devices displayed induced residual stresses, due to the bonding agent, on the order of -1900με. Upon spot welding of the shim onto a test specimen, tensile residual stresses were observed with an approximate value of +635με. Some chirping effects were observed that resulted in the spectral broadening of the FBG reflectivity envelope.

A strain gauge factor of 1.25pm/με was observed with a temperature sensitivity of 24.37pm/°C. The sensor's behavior and response was linear, without any hysterisis and repeatable measurements.

However, further worked is needed to minimize the residual stress effects as well as the increased in intrinsic temperature sensitivity. The aluminum oxide sprayed sensors are still to be tested. We plan to modify the formulation of the bonding agents to tailor a more appropriate net coefficient of thermal expansion. In addition, we will explore ways to reduce the chirping effects introduced by the agent, metal shim and spot welding process. A systems approach will be taken to evaluate all elements of the measuring system to ensure the best operating parameters with regards to overall temperature range, humidity, and water immersion applications.

Finally, we will carry out future work combining the packaging process described in this work with CCGs to develop true high-temperature resistant FBG strain sensors with capabilities for continuous operation up to 800 °C.

## 5. REFERENCES


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