光纤光栅传感器金属化保护及钎焊嵌入 42CrMo 钢

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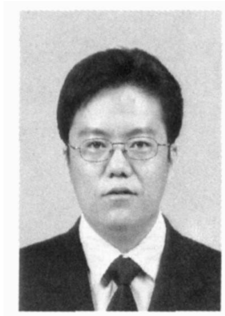
李玉龙

摘　要：针对光纤光栅传感器保护方面及向金属中封装嵌入方面现存的问题，采用化学镀和电镀结合的方法对光纤光栅传感器进行镀镍金属化保护，随后用钎焊的方法将传感器嵌入 42CrMo 结构钢中，从而获得智能金属结构。结果表明，镀层与传感器结合界面无缺陷，镀镍金属化使光纤获得了良好的保护，为后续钎焊嵌入金属做好了准备；钎焊对传感器影响较小；对钎焊后获得的智能结构进行了温度监测，表明传感器的灵敏度提高 1 倍，温度与波长变化成线性关系。

关键词：光纤光栅；智能金属结构；金属化；钎焊
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0　序　　言

光纤光栅传感器（FGB）具有不受电磁干扰、信号带宽大、灵敏度高、易于复用、重量轻、结构紧密、适合在高温、腐蚀性或危险性环境中使用等优点。这种传感器在航空航天、军用战车、核反应堆、大型建筑、矿山、油井等特殊场合的安全检测方面具有极为广泛的应用前景[1－3]。

将光纤光栅传感器集成在基体材料中获得的智能结构能感知外界或内部状态与特性变化，并能根据变化的具体特征对引起变化的原因进行辩识，从而采取相应的最优或近优控制策略以做出合理响应。具体地说该结构具有检测（应变、损伤、温度、压力及各种制导光源）、通信（数据传输）、动作（改变结构外形和结构应力分布、改变电磁场及光学反射能力、数字选择能力）等功能[4,5]。

虽然智能结构的应用前景十分广泛，但目前国内外以金属材料为基体的智能结构还很少，最为关键的原因就是传感器嵌入金属中非常困难，一般金属的熔化温度很高，传感器难以经受高温的破坏[6,7]。

作者提出采用化学镀和电镀结合的方法对光纤光栅传感器进行镀镍金属化保护，随后用钎焊的方法将传感器嵌入 42CrMo 结构钢中，从而实现金属结构的智能化，具有重要的理论意义和广阔的应用前景。内容包括光纤传感器的金属化保护（化学镀和电镀）；传感器金属化后在金属构件中的钎焊嵌入试验；传感器嵌入后获得的智能金属结构传感性能的研究。

1　光纤光栅传感器的金属化保护

普通光纤的主要成分是石英，即 SiO_2，直径在 125 μm 左右，光纤本身的强度较低，特别是切向抗弯能力较差，写入光栅以后光纤光栅传感器变得更为脆弱容易被破坏。将光纤光栅传感器嵌入到金属构件中，需要对其进行有效的金属化保护。国内外进行了较多的金属化保护方面的研究，美国斯坦福大学李晓春等人[6] 采用磁控溅射的方法对光纤光栅进行预金属化再电镀镍保护；芬兰的 Sandlin 等人[8] 采用化学镀银使裸光纤光栅金属化后进行再电镀镍的保护；武汉理工大学郭明金等人[9] 对光纤光栅采用化学镀镍再镀金的保护。上述这些方法保护有效，提高了传感器灵敏度，但普遍成本较高，操作比较复杂。采用化学镀和电镀相结合的方法对光纤光栅进行镀镍保护成本低，简单易行。具体操作规程（具体配方略）为：(1) 预处理，去保护层 →除油污 →敏化 →活化。(2) 化学镀镍。(3) 电镀镍。图 1 为化学镀镍与电镀镍光纤光栅传感器的典型宏观照片，图 2 为金属化保护后的截面图。

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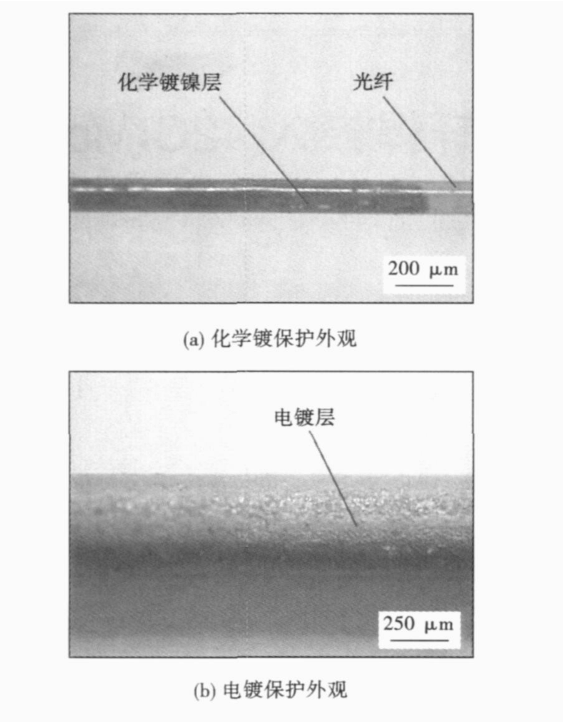

图1 金属化保护后的光纤光栅传感器外观

Fig. 1 Out view of metallization results for FBG

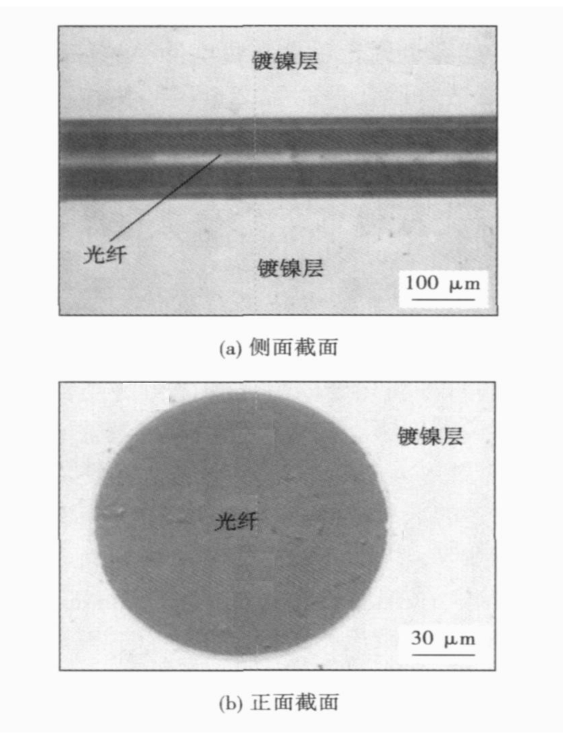

图2 传感器保护后的截面金相微观形貌

Fig. 2 Micrographs showing section of metallized FBG

从图1中可见化学镀镍层为厚度10 μm左右的光滑平整的金属薄层，而电镀层的厚度更容易控制，根据需要可以是几十微米也可以是几毫米。如图2所示，从截面金相图中可见光纤与化学镀镍层之间结合紧密，化学镀层与电镀层之间混合一体分不出边界。由此可见，化学镀、电镀结合金属化的保护方法为FBG后续的钎焊嵌入金属做好了准备。

2 光纤传感器钎焊嵌入金属基体

目前光纤智能材料结构中应用最广泛的是以复合材料为基体的智能复合材料结构，国内外的研究人员正在大力研制智能金属结构。将光纤传感器集成到金属材料中就获得了智能金属结构。智能金属结构的获得方法可以是多种多样的，但是由于一般工程应用的结构金属材料的熔点都相对较高，例如碳钢的熔点超过1 400 ℃，铜合金的熔点超过1 000 ℃，如此的高温即使是抗高温的光纤也是难以承受的。如果采用钎焊的方法，将金属化的光纤进行钎焊嵌入金属构件中，那么问题就迎刃而解了。钎焊可以通过优选不同种类的钎料在较低的温度下进行；感应加热钎焊可以实现快速升温和快速降温，对光纤承受高温的时间可以很短；通过温度场的模拟可以实现对温度场、升降温速率的控制，以防止光纤在升降温过程中受较大的热应力作用而发生破坏。正是由于钎焊的上述优点，很适合用于将镀有保护层的FBG嵌入金属基体中。

试验采用烙铁钎焊嵌入方法，采用的钎料为Sn-4Ag-3Zn钎料。烙铁钎焊是利用烙铁头积聚的热量来熔化钎料，并加热钎接处的母材而形成钎焊接头的一种钎焊方法。试验采用上海紫栅光电有限公司生产的波段为1 532 nm的FBG—A1532.0光纤光栅，光栅部分长10 mm。金属基体为直径约为25 mm，高30 mm的圆柱形42CrMo钢。在42CrMo钢中心处预先加工一个直径2 mm的通孔；在通孔内预置钎料，烙铁加热使钎料均匀涂敷到孔的内壁和镀镍金属化的光纤；将光纤置于孔内再进行加热，钎料熔化凝固即可。试验获得的智能结构雏形如图3a所示；温度传感信号检测后，正面切开、研磨、抛光并进行体式显微镜金相观察可见钎料与镀镍层、42CrMo钢基体结合良好，如图3b所示。

3 温度传感信号检测

单模的裸光纤光栅传感器在单纯温度变化下的传感模型为

$$\frac{\Delta\lambda_B}{\lambda_B}=S_T\Delta T \tag{1}$$

式中：λ_B为光纤光栅中心波长；S_T为光纤光栅传感器的灵敏度；T为温度。

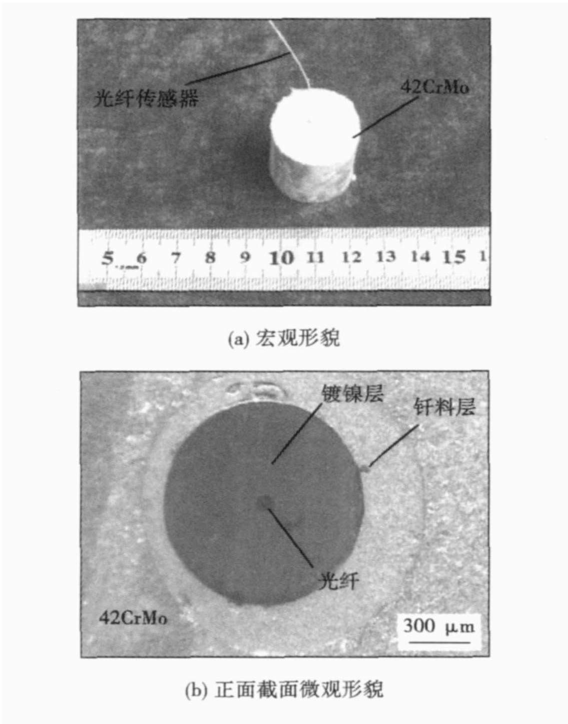

图 3　光纤光栅传感器钎焊嵌入 42CrMo 钢基体

Fig. 3　FBG embedded in 42CrMo using soldering method

其灵敏度可表示为

$$S_T = \frac{\Delta\lambda_B}{\lambda_B \Delta T} = \alpha_l + \xi \qquad (2)$$

式中：α_l 为光纤光栅的线膨胀系数；ξ 为光纤光栅的热光系数。

从式(1)中可知，理论上光纤光栅的中心波长的变化与温度变化呈线性关系；由式(2)可知，裸光栅中心波长随温度变化的灵敏度为一常量。FBG 的主要参数值由光纤制造商美国康宁公司和 FBG 制造商上海紫栅光电技术有限公司提供，其主要参数值为线膨胀系数 α_l 为 5.5×10^{-7} ℃，热光系数 ξ 为 6.3×10^{-6} ℃，中心波长 λ_B 出厂值为 1 532.0 nm。代入式(1)中可得理论上波长随温度的变化率为 10.49 pm/℃。将金属化的 FBG 钎焊嵌入 42CrMo 钢，整体置入恒温干燥箱在 220 ℃恒温 4 h 进行热处理，以消除钎焊过程中的热应力。随后在恒温箱中进行温度传感试验，温度从 30 ℃开始加热，一直加热到 170 ℃，用光纤光栅网络分析仪记录反射波长值，每分钟记录一次数据，实际上光栅分析仪扫描 100 次/s，每次记录的数据为该一时段(1 min 内)多个数据的电脑自动记录平均值。当到达设定温度值时，检测的波长趋于恒定值时才可以开始纪录，开始记录后在每个温度下停留 10～15 min，记录波长数据并取平均值。温度传感试验装置包括光纤光栅网络分析仪(型号 FONT—2004B)、恒温干燥箱。对测得的数据进行线性拟合，得到试验结果如图 4 所示，其中 A 代表 FBG 初始反射波长，B 代表 FBG 反射波长随温度的变化率，Y 为 FBG 金属化保护并嵌入后的反射波长。由图 4 可知，嵌入后的 FBG 波长移位与温度变化近似成线性关系，其波长随温度的变化率为 21.8 pm/℃。可见，经金属化保护和钎焊嵌入 42CrMo 钢后传感器的温度灵敏度提高了 1 倍，而且这种钎焊嵌入式封装的结构可以在高温下工作，而不像一般的有机物封装其工作温度多数低于 120 ℃。对于钎焊嵌入式封装来说，如果采用高温光纤光栅传感器，那么可以用高温钎料对其进行封装，从而使获得的金属结构可以在更高的温度下工作。

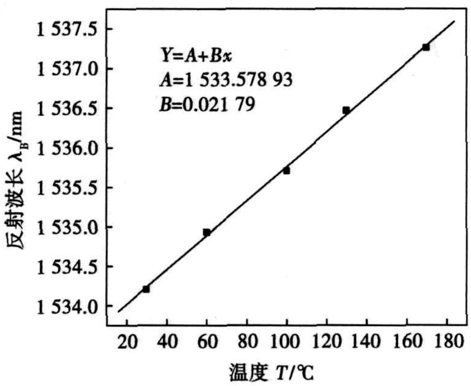

图 4　反射波长随温度变化检测值拟合曲线

Fig. 4　Fitting curve for relationship of temperature and reflection wavelength

4　结　　论

(1) 采用化学镀镍和电镀镍相结合的方法可以有效地保护光纤光栅传感器，为后续钎焊嵌入做准备。

(2) 用钎焊方法成功地将金属化的光纤光栅传感器钎焊嵌入 42CrMo 结构钢中，获得了智能金属结构的雏形。

(3) 对获得的智能金属结构进行了温度传感信号检测，温度灵敏度为 21.8 pm/℃，比光纤光栅本身灵敏度提高约 1 倍。

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ture, holding time and copper matrix on the joint microstructures, shear strength and interface reactions. The joints with shear strength close to 90 MPa could be achieved by brazing with AgCuTi at the temperature of 850—900 ℃ and the holding time of 20—60 min. Lower or higher temperature and shorter or longer holding time are detrimental to joint strength. The joint is consisted of Cu/Ag(Cu), Cu(Ag, Ti)/Cu_3Ti_3O(TiO_2)/Al_2O_3. The main product in the reaction layer was Cu_3Ti_3O, and TiO_2 was observed at certain parameters. The effects of copper matrix on the joint microstructures were different based on the parameters.

Key words: high purity alumina ceramic; oxygen-free copper; brazing; shear strength; microstructures

Wettability of two kinds of Pd—Ni brazing filler metals on Si_3N_4 ceramic Chen Bo, XIONG Huaping, MAO Wei, LI Xiaohong (Lab. of Welding and Forging, Beijing Institute of Aeronautical Materials, Beijing 100095, China). p57—60

Abstract: The wetting behavior of PdNi—(15—22)V and PdNi—(16—24)Cr on Si_3N_4 was studied by the sessile drop method. Results show that there are differences in the melting point and the wettability between PdNi—(15—22)V and PdNi—(16—24)Cr, and small contact angle and excellent interface are obtained using the latter. In the interfacial layer with PdNi—(16—24)Cr filler metal, Cr diffused to Si_3N_4 and resulted in the reaction products of Cr_2N phase. Diffusion of Cr to the base material improved the wettability of brazing filler metal.

Key words: ceramic; reaction layer; wettability; brazing filler metal

Dynamic simulation of isothermal solidification in steel/Cu/steel system rolling-diffusion bonding process LI Hong, LI Zhuoxin (School of Materials Science and Engineering, Beijing University of Technology, Beijing 100022, China). p61—64

Abstract: Rolling-diffusion bonding experiments were performed on steel/Cu/steel system using 50 μm thick copper as interlayer. The effect of plastic deformation on bonding strength and interlayer thickness was investigated. Based on experiments, the kinetics of isothermal solidification was systematically studied. And a numerical model of isothermal solidification time was developed. The results show that the isothermal solidification time is obviously reduced due to the effect of plastic deformation. A reasonable isothermal solidification time was obtained when an effective diffusion coefficient was used, indicating the intercrystalline and grain boundary diffusion of Cu in steel play an important role. The evolution of interlayer thickness indicates a good agreement between the calculation results and experimental measurement.

Key words: rolling-diffusion bonding; plastic deformation; isothermal solidification; kinetic simulation; effective diffusion coefficient

Effect of alloying elements on microstructure and property of AgCuZnSn brazing alloy LI Zhuoran, JIAO Ning, FENG Jicai, LU Chenghong (State Key Laboratory of Advanced Welding Production Technology, Harbin Institute of Technology, Harbin 150001, China). p65—68

Abstract: The Sn, Ni, P were added into AgCuZnSn brazing alloy. And the effects of Sn, Ni and P on the microstructure and property of AgCuZn cadmium-free brazing alloy system were investigated. The results showed that the wettability of the brazing alloy was improved with the addition of Sn. The addition of P could decrease the interfacial tension between liquid brazing alloy and specimen, and the wettability and fluidity were also improved. The microstructure of AgCuZn brazing alloy was consisted of Cu-rich phase, CuZn intermetallic compound, $Cu_{5.6}Sn$ intermetallic compound, $Cu_{40.5}Sn_{11}$ intermetallic compound and Ag-rich phase. Dendrite that formed in the alloy microstructure make brazing alloy friable after the addition of Sn. The black Ni_3P compound was generated when Ni was added, and make microstructure homogeneous. The gray Cu_3P compound was generated when P was added.

Key words: brazing alloy; microstructure; wettability

Fiber bragg grating sensor metallization and embedding into 42CrMo steel by soldering LI Yulong, FENG Yan, ZHANG Hua, PENG Gang (Key Laboratory of Robot &Welding Automation, School of Mechanical &Electrical Engineering, Nanchang University, Nanchang 330031, China). p69—72

Abstract: To solve the problem of fiber bragg grating(FBG) sensor protection and embedding in metal, FBG was protected with nickel coating by using chemical and electric plating method. The metallized FBG was then embedded into 42CrMo steel successfully and a smart metal part was acquired. Experiment results show FBG was protected successfully with the nickel layer, and there were no defects at the FBG/nickel layer interface. The heat did not wreak the FBG during soldering process. Temperature monitoring results show the temperature sensitivity of FBG was increased twofold after metallization and soldering, and the temperature change was linear with reflection wavelength.

Key words: fiber bragg grating; smart metal structure; metallization; soldering

Interface character of high-strength graphite and copper joints brazed with Ti-based amorphous filler metal XIE Fengchun, HE Peng, FENG Jicai (State Key Laboratory of Advanced Welding Production Technology, Harbin Institute of Technology, Harbin 150001, China). p73—76

Abstract: Graphite has been widely used in nuclear industry. Joining of graphite and copper can improve neat conduction of structure, so bonding of these two materials is a key technology needed to be solved. Copper and high-strength graphite were brazed with amorphous TiZrNiCu filler metal in vacuum circumstance, and the effect of parameters on the interface was studied. The results show that fracture occurred in graphite during tensile and shear