Fabrication of smart cutting tools with embedded optical fiber sensors using combined laser solid freeform fabrication and moulding techniques

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Abstract

To realize the concept of smart tools, embedding of fiber optic sensors in the metallic structure of a cutting tool with combined laser solid freeform fabrication (LSFF) and moulding is presented in this paper. Metallic parts with embedded optical fiber sensors are capable of monitoring physical parameters like force and temperature. These sensors are advantageous relative to other conventional electric and electromagnetic sensors due to their light weight, immunity to external electromagnetic fields, small size, long-term durability, and long-range linearity. In the present work, the optical fibers (e.g., fiber Bragg grating sensor, single-mode fiber optics) are moulded under tensile forces within a mild steel casing filled by Sn–Pb to fabricate a protective layer around them. Afterwards, LSFF is utilized to deposit tungsten carbide reinforced in cobalt (WC–Co) on the surface of the mild steel component. The performance results, in which the sensor exposed to a light bandwidth, show that the maximum light power loss after embedding is about 21% implying that the fiber is not damaged during the embedding process. Also, the sensor output has a linear characteristic under compression loadings indicating that the debonding of the fiber from the protective layer is not probable. The produced samples are examined by scanning electron microscopy and X-ray diffraction to assess the physical properties of the tool. Microstructural images reveal no cracks and porosity around the fiber indicating a good bonding between the fiber and the surrounding media. Material characterizations of the manufactured tool are also discussed.

Keywords: Smart cutting tools; Fiber optic sensors; Laser solid freeform fabrication; Tungsten carbide reinforced in cobalt

1. Introduction

In situ measurement of loads applied to tools (e.g., cutting, drilling, mould and die) is essential to high precision machining and health monitoring. Tool health monitoring and precision machining necessitate real-time awareness of the applied thermal and structural loads. Using conventional sensors attached on the surface of the tools, one can measure the physical loads applied to the tool. However, the measurement is only limited to external surfaces. Embedded sensors within the metallic structure of tools can monitor the physical parameters not accessible by ordinary sensors. The signals from the embedded sensors can be processed to obtain the thermal and/or structural loads applied to the tool in-service. The obtained data can be used as feedback signals in a real-time control system to improve the performance of the tool. They can also be used for failure detection in cutting tools in-service. Among all available sensors, optical fibers can be effectively used to monitor thermal and structural loads. Compared to conventional electric and electromagnetic sensing devices, optical fiber sensors, made of silica ($\text{SiO}_2$), are advantageous. They have light weight, small size, long-term durability and long-range linearity. Moreover, they are robust to external electromagnetic fields and disruptions [1]. These capabilities prompt the development of a technique to embed optical fibers inside metallic structures to realize the concept of smart tools.

Embedding of optical fibers inside concrete and composite materials for structural health monitoring has been...
reported in recent years [2–4]. Li et al. presented the methodology of embedding of optical fiber Bragg grating sensors inside metallic structures with shape deposition manufacturing (SDM) incorporating laser material processing. In this technique, electrodeposition was used to fabricate a thermally protective layer around the fiber prior to SDM [5].

The present work describes the deployment of a combined technique to embed optical fibers (i.e., fiber Bragg grating) in the metallic structure of a cutting tool to realize the idea of smart tools. Laser solid freeform fabrication (LSFF) is utilized for the embedding process to deposit tungsten carbide reinforced in cobalt (WC–Co) which is a common material in the fabrication of tools. As the LSFF process is equipped with a laser heat source, to resolve the problem associated with elevated temperatures, the fiber sensor must be coated with a protective material before embedding. To make the protective layer, a low melting point metallic alloy is selected to mould the fiber optic.

To study the influence of the proposed embedding process on the performance of the optical fiber, the optical response of the embedded fiber was compared to that of the bare fiber. The results showed that the fiber could pass the light bandwidth after embedding with minor losses. Consequently, the embedding was successful and without any damage to the fiber. To study the performance of the prototyped tool, the part with embedded fiber Bragg grating was tested under compression loadings. To investigate the microstructure of the embedded fiber, surrounding media and the deposited WC–Co, the samples were cut, polished and examined with optical and scanning electron microscopy (SEM). The micrographs showed that there was a good bonding without cracks and porosity between the fiber and the surrounding material. In addition, the process did not damage the fiber external circular surface. The deposited WC–Co was examined by XRD to determine the available phases. Microhardness of the WC–Co layer was measured by a Vickers microhardness tester, and the results were compared with those of existing cutting tools. In addition, the bonding strength of the deposited WC–Co layer was determined by compression tests.

2. Materials

WC–Co is a common hard material widely used in making cutting tools. This material is often known as cemented carbide or sintered carbide. Due to the existence of both tungsten carbide (WC) and cobalt (Co), this material has a combination of hardness and toughness together. In WC–Co, cobalt acts as a matrix holding the hard particles of tungsten carbide. LSFF can be used to deposit this material on mild steel to create hard-face on the cutting tools.

Optical fibers are sensitive to high temperatures; temperatures above 1000 °C can permanently damage the optical fiber. As a result, LSFF, which is a high temperature process, cannot be used directly in the embedding process. To resolve this issue, an initial protective layer must be fabricated around the fiber optic using low temperature processes. Two methods can be considered for the fabrication of the protective layer around the fiber. One is electrodeposition technique (i.e., electroplating) and the other one is moulding. Since optical fibers are not conductive, the electrodeposition method needs the pre-deposition of a thin layer of a conductive material on the fiber. Sputtering is one of the possible techniques utilized for this purpose. In general, electrodeposition techniques require expensive devices for making the protective layer. Another recognized method is moulding, in which a low temperature molten metal is moulded around the fiber [6,7]. In this method, a low melting point material with good adhesion with the fiber is melted and poured in a mould while a fiber sensor is pre-placed inside the mould. The drawback of this method is the formation of residual stresses after solidification. This is attributed to the difference in the thermal expansion of the molten material and the fiber optic. To reduce the effect of residual stress, the fiber can be held under tension during the moulding process. The material used in this technique should have not only a low melting temperature but also a good adhesion to silica. The material chosen in this research is Sn–Pb alloy (65 wt% Sn). The melting point of Sn–Pb (65 wt% Sn) alloys is low (i.e., 185 °C), which is suitable for the embedding process. Moreover, it has a good adhesion to silica. This is due to the high wettability of silica by these metals. This can be described by metal–oxide interaction between Sn/Pb and O²⁻ in silica [8]. Coating of fiber optics with molten tin has also been reported [6,7].

3. Experimental procedures

The steps of the embedding process are shown in Fig. 1. The embedding process is a combination of moulding and LSFF. To protect the fiber from thermal damage, a protective layer is made on the fiber prior to LSFF. The method used in this work is moulding in which the fiber is coated with Sn–Pb alloy (65 wt% Sn).

LSFF setup consists of a high power pulsed Nd:YAG laser system integrated with a powder feeder, CNC table and a vision based real-time process control system. In this setup, the workpiece is mounted on the CNC table. The table, controlled by a closed-loop system, moves the workpiece beneath the laser beam. The laser beam melts a thin layer of the substrate and creates a melting process zone. The metallic powders are injected to the process zone through a nozzle connected to a powder feeder [9]. After solidification, a thin layer of secondary material forms on the substrate (Fig. 2).

Fig. 3 presents the schematic arrangement of the LSFF setup. In the present study, a 1 kW pulsed Nd:YAG laser was used with a defocused laser beam of 1.5 mm in
diameter delivered to the substrate. The powder feeder nozzle was set at the angle of 55° with respect to the substrate surface. In the experiments, argon gas was used as both shielding and carrier gas.

Single mode optical fibers were used for embedding. The optical fiber is a cylindrical waveguide with a central core surrounded by a cladding layer. Both the core and the cladding are made of fused silica (SiO₂) with different refractive indices. Dopants like GeO₂ are added to the core of the optical fiber to increase its refractive index [10]. Due to the difference between the refractive indices of the core and the cladding, the electromagnetic waves passing through the core are reflected in the core-cladding interface and confined in the core. In single mode optical fibers, the core has a diameter of 8–12 μm and the cladding outside diameter is 125 μm. To protect the silica fiber against physical damage an outer coating of acrylate is also fabricated around the cladding during the fiber production process. One type of optical fibers used for sensing application is fiber Bragg grating (FBG). FBG is a modulation of the index of refraction along a given length of the core of single mode optical fibers. Functioning like a filter, a FBG reflects a portion of input broadband light at a single wavelength, called Bragg wavelength, and transmits the remaining one. The spectral response of a FBG
sensor exposed to thermal and/or structural loads differs from a load-free sensor. Consequently, FBG can be considered suitable for measurement of structural and thermal static and dynamic fields such as temperature, strain and pressure [1].

Compared to conventional electric and electromagnetic sensing devices, FBGs are quite advantageous. They have light weight, small size, long-term durability and long-range linearity. Moreover, they are robust to external electromagnetic fields and disruptions [1].

To conduct the embedding process, the acrylate coating of the fiber was first removed. Coating removal was performed by a chemical stripping process. The fiber was immersed in a container of acetone for 15 min. Acetone dissolved the acrylate coating, leaving the exposed fiber. In this way, the fiber was not exposed to stress during stripping.

The next step in the embedding process was the fabrication of the protective layer. To do so, a mould from mild steel was made and the fiber was mounted under a tensile force. The Sn–Pb alloy was melted and poured in the mould. After solidification, a protective layer of Sn–Pb alloy and mild steel was made around the fiber. In order to reduce the effect of residual thermal stresses during solidification, a constant tensile stress of 80 MPa was applied to the fiber during the process.

Table 1
Optimized process parameters for LSFF

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser energy</td>
<td>J</td>
<td>2–5</td>
</tr>
<tr>
<td>Pulse frequency</td>
<td>Hz</td>
<td>30–70</td>
</tr>
<tr>
<td>Pulse width</td>
<td>ms</td>
<td>2–7</td>
</tr>
<tr>
<td>Scan speed</td>
<td>mm/s</td>
<td>2–5</td>
</tr>
<tr>
<td>Powder feed rate</td>
<td>g/min</td>
<td>2–4</td>
</tr>
<tr>
<td>Inert gas flow</td>
<td>mm³/s</td>
<td>3–6</td>
</tr>
</tbody>
</table>

After making the protective layer, LSFF was used to deposit layers of WC–Co on mild steel. In order to optimize the process parameters, a number of tracks were deposited with different process parameters. First, the deposited tracks were examined visually. The samples having uniform tracks without porosity and carbon formation on the surface were selected and their cross-sections were examined. The process parameters, leading to higher deposition rate with track aspect ratio more than five was chosen. Subsequently, multilayer overlapped tracks were deposited with the chosen process parameters. Table 1 summarizes the range of the optimized process parameters used in the experiments.

Through the above-mentioned procedure, a tool was built, as shown in Fig. 4(a). The protective and the deposited layers are seen in the figure. The fiber and its optical connector for connecting the fiber to the light source and photosensitive cell to measure the light intensity are also shown in the figure. In general fashion, the formed tools are machined to create the desired geometry and cutting edges. Fig. 4(b) shows a typical smart cutting tool after machining.

4. Results and discussions

To study the effects of the developed embedding process on the performance of the fiber, its optical response was assessed before and after embedding. In both cases, one end of the fiber was connected to a light source with sweeping wavelength and the other end was connected to a photodetector cell. The instrument used for this purpose was an interrogation system manufactured by O/E Land Co. The source emitted infrared light with wavelengths in the range of 1550–1555 nm and the photodetector module measured the power of the light passing through the fiber. Fig. 5 shows the normalized power against the wavelength for the bare and the embedded fiber. As shown in the figure, the light transmitted through the embedded fiber
indicates that no damage occurred during the embedding process. However, the power intensity in the embedded fiber is less than that of the bare fiber. The optical loss is plotted in Fig. 6. According to this curve, the maximum loss is 21% at the wavelength of 1551.5 nm. This may be due to some minor residual stresses that were not eliminated by the tensile stress on the fiber during the process. Due to opto-mechanical properties of optical fibers, the stresses applied to the fibers can change their refractive index [1]. The change in the refractive index can affect the propagation of light and the power intensity along the fiber [11].

Cutting tools with embedded FBG sensor were also prototyped. To study the performance of the manufactured tools, a sample was loaded in a universal tensile test machine (Instron 4206). The sample was mounted in such a way that the sensor was entirely in compression during the test. The test setup is shown in Fig. 7. The spectral response of the sensor was monitored with a sm125-200 FBG interrogation system made by Micron Optics Inc. Fig. 8 shows the reflectivity of the sensor at different loading conditions. The loads were recorded from the load cell installed in the machine. As shown in this figure, the FBG reflectivity peak shifts to lower wavelengths with increasing load. It is also seen that the reflectivity signal broadens and the maximum reflectivity decreases as the load on the sample is increased. This can be attributed to the Poisson’s effect resulting in transverse loads [1].

Fig. 9 shows the peak location shift ($\Delta \lambda$) against the applied load. As illustrated in the figure, the shift in the peak wavelength has a linear trend. The peak wavelength location varies from 0 in no-load condition to 460 pm at the load of 7000 N. This behavior is resulted from the long-range linear characteristic of FBG sensors and linear structural properties of the metallic part. It can also be inferred that the debonding of the fiber from the protective layer and/or debonding of the protective layer from mild steel is not probable, because any significant debonding may cause deviation from linear trend in the shift in reflectivity peak wavelength. The measurements were carried out several times indicating good repeatability as well as the absence of any residual stresses within the fabricated tool.

The produced samples were cut, polished and examined with optical and scanning electron microscope. A Jeol:JSM-6460 scanning electron microscope equipped with Oxford Instruments’ INCA X-ray chemical analysis instrument was used for SEM. Fig. 10(a) demonstrates the microstructure of the sample cross-section taken by SEM. The optical fiber surrounded by Sn–Pb alloy and the deposited layers of WC–Co can be easily observed in this figure. Fig. 10(b) shows a close-up view of the fiber and the surrounding...
material. This figure reveals that there is a good bonding between the protective layer and the fiber. As shown in the figure, cracks and porosity are not observed around the fiber. In addition, the external surface of the fiber was not damaged during the process, and the fiber retains its round shape after embedding.

XRD tests, using a 2 kW (40 kV and 50 mA) SA-HF3 X-ray generator machine and Cu-Kα radiation, was employed to determine the types of the phases that formed in the deposited WC–Co layer. The results are shown in Fig. 11. This analysis confirms the presence of WC and Co phases in the deposited zone. However, the peaks for other metallic carbides, such as W3C, Co3W3C, and Co6W6C are not present.

The microhardness of the deposited WC–Co was measured by a Vickers microhardness tester. The test was performed on the cross-section of the deposited material with a MHT Series 200 LECO tester and a load of 1000 g. The measurement results are plotted in Fig. 12. The results show the hardness against the distance from the WC–Co and mild steel interface. Its value starts from 200 VHN in mild steel region and reaches 1750 VHN on the top side of
the WC–Co layer. The microhardness in the deposited WC–Co layer is between 1250 and 1700 VHN, which is comparable to the conventional WC–Co samples [12]. This harness value indicates that the fabricated part has the required hardness for a typical cutting tool.

The adhesion/cohesion strength of the deposited layer of WC–Co was also determined. The strength was determined by compressive testing of the specimen using Universal Testing Machine (Inspron model: 5556). The sample fractured at the stress of 60 MPa. Observations after testing revealed that the fracture occurred at the interface. It was concluded that the failure is mostly at the interface. Before failure, a strain of about 30% was observed. This indicates that the nature of the interface is more towards ductile [13].

5. Conclusions

Fabrication of a metallic part with embedded optical fibers using combined LSFF and moulding was introduced throughout this paper. The manufacturing process is a combination of moulding, for making a protective layer around the fiber, and LSFF, for the deposition of WC–Co. For the moulding process Sn–Pb alloy with low melting.
point and excellent adhesion to silica was selected. In the LSFF process, the system parameters were optimized in order to deposit layers free of cracks and porosity. The performance of the optical fiber in passing the optical waves was also examined. The results showed that the embedded fiber could pass the optical waves. As a result, the fiber was not damaged during the embedding process. Also, the performance of a manufactured tool with the embedded fiber Bragg grating sensor was investigated. The results showed that the sensor retained its linear behavior after embedding and it could easily monitor the stresses applied to the tool when loaded. The manufactured samples cross-sections were examined with SEM. The results did not reveal the formation of cracks and porosity around the fiber. Also, the round shape of the fiber did not change after the embedding process. The WC–Co layer was examined by XRD. The results showed that the only available phases in the deposited layers were WC and Co, and no intermetallic phase formed during the process. The microhardness of the deposited layer was measured and compared with conventional cemented carbide tools. Finally, the bonding strength of the deposited layer was determined in a compression test, and it was concluded that the failure is mostly at the interface. For future work, efforts are being made for the further calibration of the embedded sensors and the assessment of the performance of the fabricated tools in-service.

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References