Thermocouple Embedding for the Production of a Substrate for Rapid Manufacturing

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Reviewed, accepted August 28, 2007

Abstract

This paper reports the results of a set of experiments testing methods to embed thermocouples during laser deposition. Various operating settings and shielding materials are explored. Temperature readings of the embedded thermocouples are compared with surface temperature readings taken by a non-contact digital pyrometer during the deposition process. Also, possibilities of using this information for system control are discussed.

1 Introduction

Many recent research studies are based on the development of fast, on-line time to time monitoring methods to evaluate the present states of critical elements in complex structures. Smart materials enable one to detect and identify potential material performance problems in the prototyping stages, before they reach criticality and substantially degrade material performance capabilities [1].

Embedded sensors provide on-line time to time data acquisition and information of certain parameters at critical locations not accessible to ordinary sensors during a process or operation [2]. This information can either be used to improve designs during the initial prototyping stages or to obtain data on the performance of the parts and components functioning and in use.

Controlling the temperature of the parts being laser deposited during the deposition process is a very important issue so as to make the grain size more consistent and uniform thereby improving the microstructure. Therefore thermocouple embedding will be a very useful application as the temperature of the substrate can be collected at time intervals and the temperature can be controlled either by heating or cooling the substrate to improve the microstructure. In this paper, we make use of the Laser Aided Manufacturing Process (LAMP), developed at the University of Missouri - Rolla, to embed the sensors [4–7, 9–13].

2 Experiments

The conditions inside the work volume of the LAMP machine require the use of a robust sensor. Hence a K-type thermocouple KMQSS with a 0.125" diameter stainless steel sheath is selected so as to withstand the extreme conditions inside the chamber of the deposition machine. This thermocouple can withstand till a temperature of 1250 °C.

However the embedding of the thermocouple is an issue, the melting point of H13 being 1450 °C and the maximum temperature that the thermocouple can withstand being 1250 °C. Therefore some kind of protective coating needs to be given to the thermocouple so as not to destroy the thermocouple during the embedding process [3].

2.1 Direct Deposition

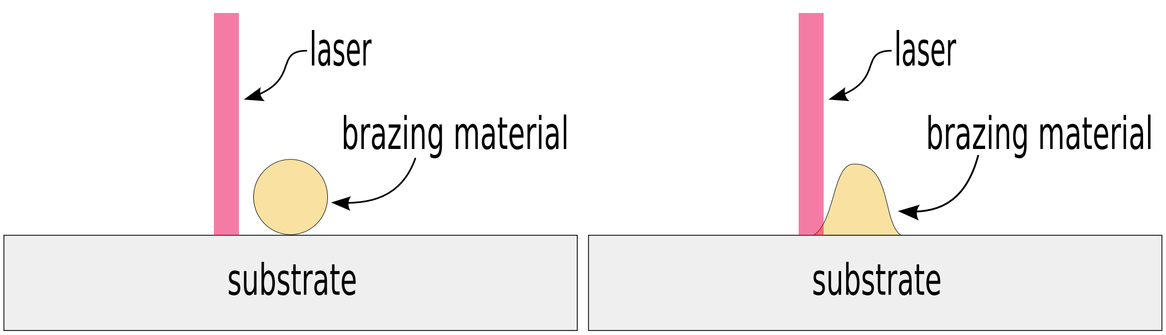
Numerous experiments are conducted to determine a suitable embedding process. Initially, an experiment was conducted to test the feasibility of directly depositing over the thermocouples. Instead of using thermocouples, nickel chromium wires are used for the experimental purposes which are much cheaper and more readily available. The melting point of nickel-chromium is comparable to the melting point of the thermocouple sheath of stainless steel being used.

In the first experiment, the laser directly illuminates the Nickel-Chromium wires. The experiments are performed for laser powers of 350, 440, 530 and 660W with a constant feed rate of 20 inches/minute. At a laser power of 350W, it is observed that there is a slight discoloration but there is no substantial change in the shape of the Ni-Cr Wire. At 440W, the wire bonded to the metal block. Melting is observed at 530W and the wire almost disintegrates at 660W. Therefore some kind of shielding material is necessary to avoid direct contact of the wires with the laser and not to destroy the wires. This needs to be applied to the thermocouple embedding process. A material with a melting point lower than stainless steel, high heat conductivity, and a high latent heat of fusion is suitable for this process. These three properties allow the shielding material to act as a buffer to protect the thermocouple and aid in bonding the thermocouple to the deposited material.

2.2 Shielded Deposition

Brazing Material - Brazing material was first selected as the material to form the bonding between the thermocouple and the substrate

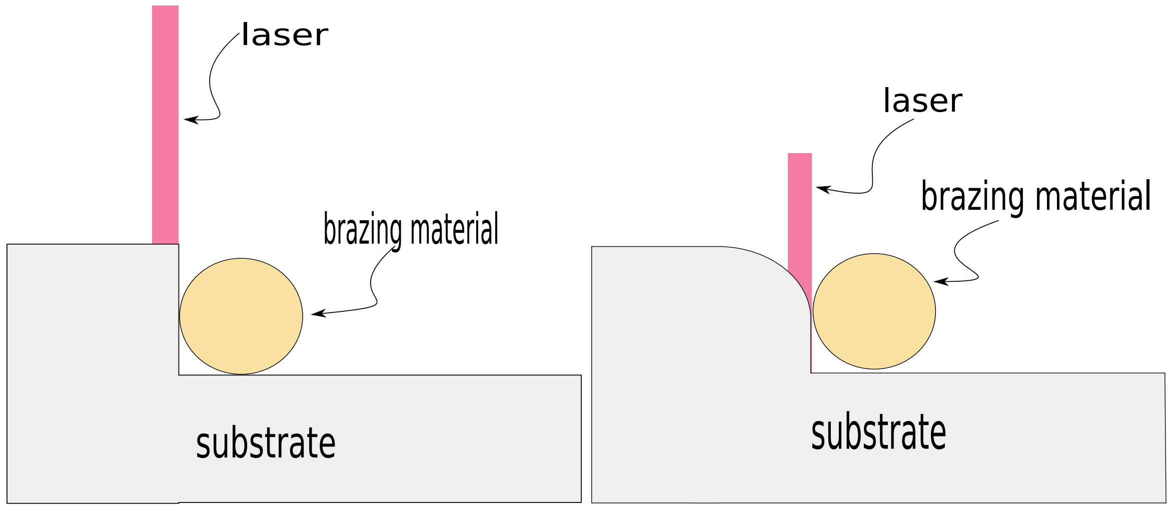
First Try - A pool of molten brazing material is created by heating the brazing material wires indirectly using laser which would then act as a bond between the tool steel substrate & thermocouple. Direct contact of the brazing material wire with the laser is avoided in this experiment as it vaporizes the zinc in brazing material. Initially the laser is hit right next to the brazing material wire and the expected result is to the melt the brazing material as the substrate gets more and more heated. This is observed only during the initial melting phase. As the molten part of the brazing material gets in contact with the laser, minor sparks are observed and fumes are also produced.



(a) Theoretical (b) Actual

Figure 1: Brazing material testing

Second Try - A step cut is prepared on the substrate with the brazing material wire placed on the lower step and the laser is hit on the edge of the top step. The expected result is to melt the brazing material due to the conduction of the heat to the brazing material from the substrate. The brazing material does not melt and due to overheating, the edge of the step disintegrates and the laser finally comes into contact with the brazing material creating minor sparks once again. The idea of using the brazing material for bonding was dropped.



(a) Theoretical (b) Actual

Figure 2: Brazing material testing with a step cut

Copper - The reason for using the copper tube is mainly because of the lower melting point of copper material (1083 °C) than H-13. This ensures that the copper tube will melt before the sheath of the thermocouple, thereby not destroying the thermocouple and also assures that the copper tube has securely fused with the thermocouple stainless steel sheath.

The thermocouple is securely placed inside a copper tube of sufficient thickness. It is then placed inside an autoclave with the connector end sticking outside the furnace. Temperature of the autoclave is set at 1045 °C. It is observed that copper rod is in a semi solid state at 1046°C (melting point of Copper 1083 °C). Copper rod fuses with the stainless steel sheath of the thermocouple. Thermocouple readings are tested and it is observed that the readings are accurate and the thermocouple is not destroyed.

Therefore we can conclude that the process of using the autoclave is repeatable.

The laser is set at 500W and feed rate at 30inches/minute. These settings are maintained for the first three layers of the laser deposition. Then the laser is set at 660W and the feed rate is decreased to 20inches/minute

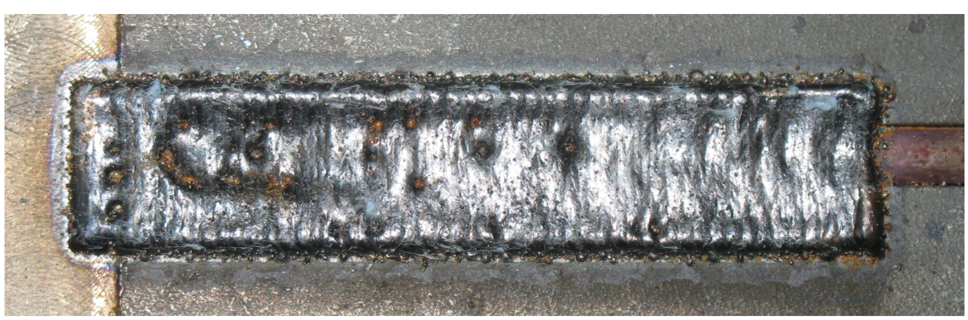


Figure 3: Embedded K-type thermocouple.

3 Observations and Results

The embedded thermocouple is cut across the cross-section to observe the bonding between tool steel and copper tube and between the copper tube and stainless steel sheath of the thermocouple. Figure 4, below, shows a cross sectional cut of the embedded thermocouple.

Figure 4: Cross section of embedded K-type thermocouple.

For the above result to occur, molten steel must have flowed around the Copper tube during deposition. As illustrated in Figure 5, the Copper tube shields the bottom of the slot from direct laser radiation.

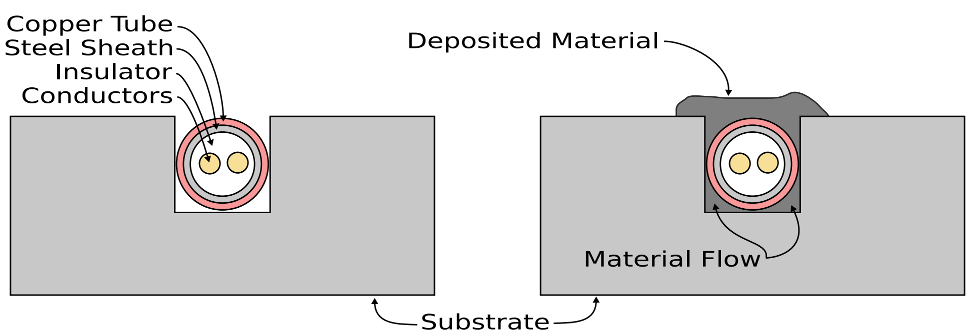


Figure 5: Material flow during the embedding operation.

Under typical deposition conditions, substrate geometry such as the slot used for the thermocouple limits the accessibilty of laser energy and/or powder delivery to the corner location. This results in a void at the corner of the slot, as shown in Figure 6.

4 Future Work

The two interfaces, between tool steel and copper and between copper and stainless steel sheath of the thermocouple, are checked by doing an EDS analysis using a Scanning Electron Microscope on the cross-sections of the embedded thermocouples to find out if a metallurgical bond is present between the tool steel and the copper tube and between the copper tube and the stainless steel sheath. This bond will be indicated by some diffusion of atoms across the original boundaries. Also of interest is the mechanism by which material flows around the Copper shielding tube during deposition. More temperature measurements will

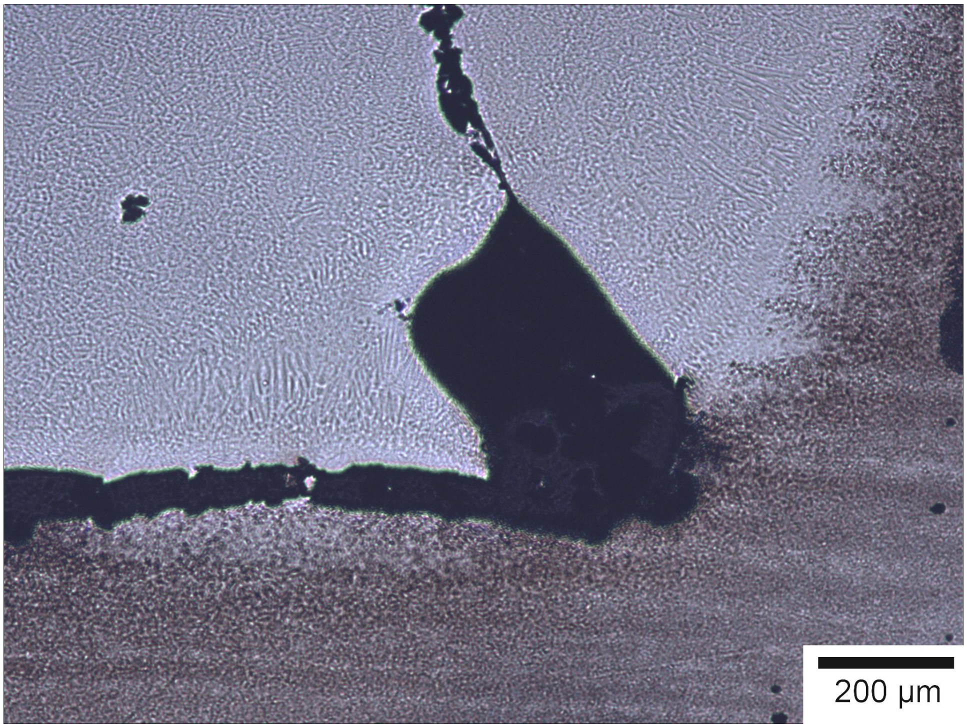


Figure 6: Corner void

need to be taken after the thermocouple embedding is done to get more data on controlling the temperature to improve the consistency of deposition microstructure [8]

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