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Process development for additive multi-material components

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Abstract

Suppliers of laser systems face worldwide competition. In order to stay on the market and remain competitive, it is necessary to improve products and processes continually. Additive manufacturing of metals has emerged as a potential technology for companies to create highly integrated and individualized products. Building on this, the subsequent step is to integrate optomechanical and thermal properties into these structural parts. This is done by combining and encapsulating optical elements like quartz lenses or laser crystals with special nickel-iron alloys and thus creating multi-material components. Furthermore, matched thermal expansion coefficients of the used materials and integrated cooling solutions are supposed to reduce mechanical stress and improve optical properties of the assembly. The objective is to develop a lean single-stage process with minimal handling of the fragile laser components. First experiments using powder-based laser metal deposition with a 680 W diode laser show success in encapsulating and bonding different materials. Microsections were used to analyze the specimens regarding structural integrity and defects.

Keywords: Additive manufacturing; multi-material; Laser Metal Deposition

1. Introduction

Laser Metal Deposition (LMD) is one of the major 3D-printing technologies for metals. Recently it evolved from a laser cladding process to additive manufacturing (AM). According to forecasts, the total market size is continuously growing with increases of the market volume up to 18% per year in the professional environment [1] [2]. AM uses new approaches in manufacturing and opens up possibilities, which surpass

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conventional manufacturing. The LMD-Process is a predominant subject of research in the aerospace and automotive field. Typical use cases are repairing and refurbishing of complex and valuable technical capital goods like compressor and turbine blades or molds and forms. Compared to the more popular laser powder bed fusion (LPBF), LMD has the unique ability to add material onto existing freeform surfaces while having a larger build volume. The former aspect allows encapsulating of other parts with printed metal. One approach here is to create multi-material components and combine structural, thermal and optical properties of different materials into a single part. These advantages make the LMD process suitable for the attempted multi-material combinations described in this paper.

State-of-the-art for fixing optical components like laser crystals and quartz lenses in optical setups are multi-part assemblies. They rely on tensioners that create a clamping force to position the component and ensure thermal conductivity. These fixtures induce unwanted mechanical stress and increase production costs due to added manufacturing expenses. Fixtures for laser crystals are commonly made from copper because of its excellent thermal conductivity. To overcome higher thermal resistance at the contact surfaces indium foil is used to connect crystal and copper. For applications with lower thermal demands, stainless steel is typically utilized to position and hold lenses.

The idea considered here is to incorporate optical components into single 3D printed metal parts. Custom cooling solutions, optimized topology and minimal handling of the fragile components are just some of the possibilities that can be integrated with the use of AM.

To achieve this, a material-system with a fitting process has to be developed. Two types of connections are evaluated. First, a material bond is analyzed and then a form-fit that encapsulates an optical element is examined. Furthermore, is presumed that the thermal expansion of the combined materials can be approximated. The results of a consequent dilatometer experiment support this assumption. With the help of specially designed experiments, the process parameters have to be determined.

2. Experimental Setup

The process development is carried out on a six axis LMD Machine with a coaxial powder feed. In principle, a laser beam melts the substrate locally and a filler material is inserted into the molten pool. This creates the direct deposition of metal on top of the substrate. In the stage of process and material development, a powder-based setup is preferred to change or alter the material composition easily. The coaxial arrangement of the laser and the powder stream removes any directional constraints during the print process. As a laser source, a Laserline LDF 650 diode laser with 940 and 980 nm wavelength and a maximum power of 680 Watt is used. The emitted light is guided to the processing head via an optical fiber and focused on the substrate. The high intensity of up to 1.75 MW/m^2 melts the substrate locally. Alongside an argon shield gas, metal powder exits the processing head through an annular opening. The powder stream hits the molten pool of metal and liquefies. The processing head moves along and the molten metal solidifies. The head itself follows a preprogrammed toolpath. A solid body is then created layer by layer. A section of the nozzle is shown in figure 1a. In addition, the connection between the quartz lens and the 3d printed structure, which is examined below, is shown schematically. The photograph in figure 1b shows the processing head while 3d printing a specimen.

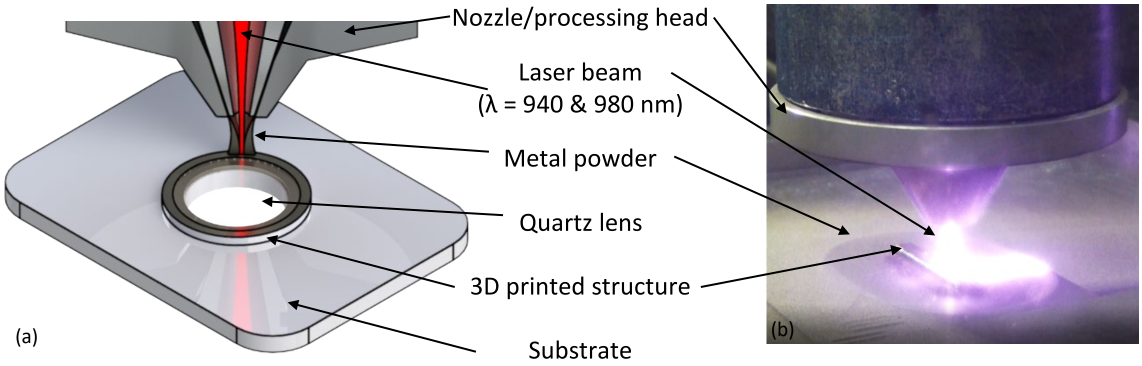

Fig. 1. Processing head while encapsulating a quartz lens (a) and a photograph of the process (b)

2.1. Experimental design

Throughout the process development, the conducted experiments were planned statistically and structured as follows:

First a material had to be selected according to thermal and mechanical properties. The selection of materials was based on literature resources and then adapted to the application. Pilot experiments with the selected metal in combination with Nd:YAG crystals were carried out to investigate the inter-material bond. Then a design of experiments was setup to evaluate the encapsulation and 3d printability for the special metal powder in order to find process parameters. The experiments were based on statistical and factorial designs generated with the software JMP. Therefore, upper and lower boundaries of the most important factors laser power, powder mass-flow and the feedrate had to be defined. To be able to quickly modify and test as many parameters as possible a python script generated the individual machine toolpaths automatically. The script is able to generate simple lines with varying parameters up to arbitrary multi-layer specimen in pursuance of parameters and its responses.

Finally, with working parameters a specimen to evaluate the thermal and mechanical properties of the developed material was manufactured and analyzed.

The printed solids were examined with microsections and porosities and structural defects were identified.

2.2. Material Selection

The thermal expansion of commonly used materials for optical assemblies differ from the material used as a laser crystal by up to 100%. These differences in expansion make a direct bond between a metal and a Nd:YAG crystal, which needed for minimal thermal resistance, critical. The thermal expansion coefficients of copper, stainless steel, molybdenum and two iron-nickel based alloys found in literature compared to a Nd:YAG crystal are shown in figure 2a. At 100°C copper has a relatively high thermal expansion coefficient of $17 \cdot 10^{-6} K^{-1}$ [3]. The coefficient of stainless steel is $16 \cdot 10^{-6} K^{-1}$ [4] is similar. In comparison, this is almost double the value of a Nd:YAG crystal with a coefficient of $8.1 \cdot 10^{-6} K^{-1}$ [5]. Therefore, temperature changes can lead to mechanical stresses due to the different thermal expansions of the materials. Based on these resources an iron-nickel alloy comparable to invar is selected. With thermal expansion coefficients of $9.45 \cdot 10^{-6} K^{-1}$ (48% nickel) and $8.05 \cdot 10^{-6} K^{-1}$ (46% nickel) [6] the compound is eligible for a direct bond. To improve the approximation at higher temperatures the nickel content is reduced to 44%. In later stages of development, molybdenum could be an option to maximize the fit at higher temperatures.

A scanning electron microscopy photography in figure 2b shows the particles of the selected FeNi44 powder. The spherical particles are made of pure iron. The irregular shaped particles are pure nickel. The predominant grain size amounts to 60 µm. The composition was verified with energy dispersive X-ray spectroscopy (EDX).

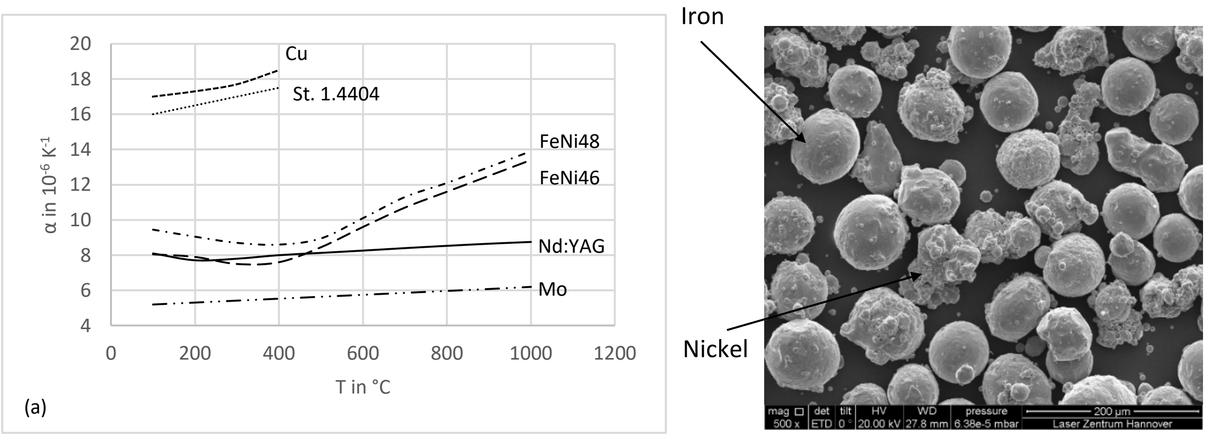

Fig. 2. Comparison of different metals (a) and scanning electron microscopy of the FeNi44 powder (b)

2.3. Specimen

For the first investigations and in order to analyze the material bond with metal two Nd:YAG crystals were submerged in molten nickel. One of the crystals was coated with a layer of titanium to use its affinity to the oxygen of Nd:YAG crystal to create a stronger bond. Regarding the process development, sets of the automatically generated specimen were printed (see figure 3a). They are designed to identify responses to the laser power, printing speed and powder mass-flow.

The encapsulation of quartz lenses was evaluated with the help of 3d printed specimen shown in figure 3b. The hatched area seen in the cross section of figure 3c depicts the 3d printed structure tapering over the lens highlighted in blue. The lens is 1 mm thick and has a diameter of 25 mm. With chosen process parameters a larger specimen has been printed. It was manufactured using the FeNi powder containing 44% nickel and 56% iron. The dimensions of the specimen were 55x10x10 mm.

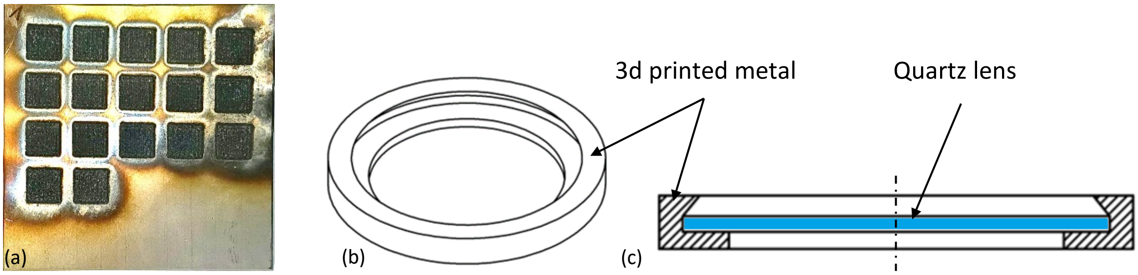

Fig. 3. Sketch (a), section (b) of the 3D printed encapsulation and (c) DOE specimen

3. Results and Discussion

With the multi-material combination of metals and optical elements in mind a Nd:YAG crystal was submerged in molten nickel metal. Microsections of the solidified metal in connection with the laser crystals can be seen in figure 4. The Nd:YAG crystal is intact and in contact with the metal. There are no defects visible inside the metal or in the crystal. The transition angle between the two materials indicates the quality of the bond. A lower angle is favorable, because it hints at a better wetting of the metal in contact to the crystal surface. Figure 4a shows the Nd:YAG crystal directly bonded to nickel metal. With an angle of 94.7° between the crystal and the nickel surface, the two components successfully bonded. Building on this, adding a one-micrometer thin layer of titanium via physical vapor deposition significantly improves the bond and lowers the measured angle to 54.9° as shown in Figure 4b.

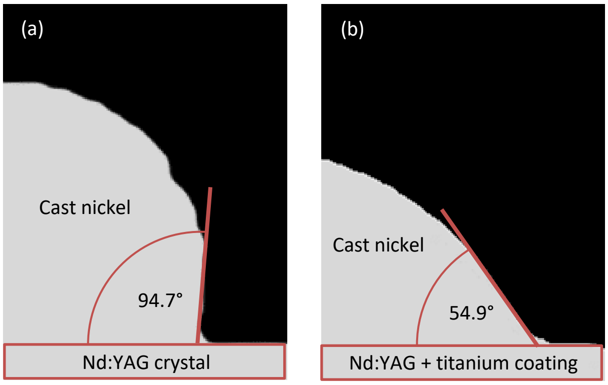

Fig. 4. Cast nickel directly bonded to a Nd:YAG crystal (a) and a specimen with titanium coating (b)

After showing that multi-material bonds between nickel based alloys and laser crystals are possible, experiments regarding the encapsulation of quartz lenses as a form-fit were carried out by LMD. In figure 5a, the lens is shown after the printing process. In this experiment, stainless steel (St. 1.4404) is used because of its better printability at overhangs. After printing, there are cracks visible close to the area where the metal tapers over the glass. These cracks originate from differences in thermal expansion of the two materials and justify the development of a special alloy. Furthermore, the heat generated by the laser partly harmed and melted the edge of the quartz glass. Nonetheless, the microsection depicted in figure 5b shows that the

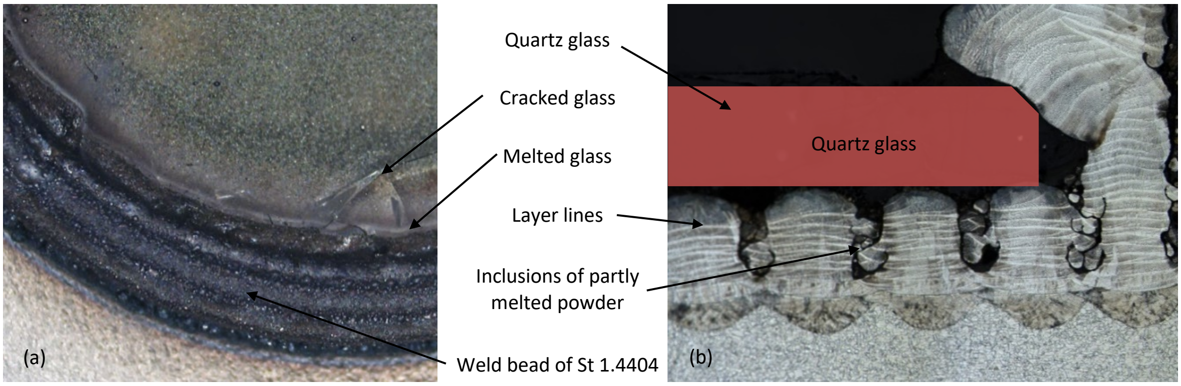

Fig. 5. Overview (a) and a microsection of an enclosed quartz glass (b)

printed structure successfully enclosed the quartz glass. The lens was held tightly in its position even without establishing a bond between the glass and the metal.
To evaluate the properties of the special iron-nickel alloy parameters for the LMD process were needed. The parameters were acquired through a full factorial design of experiments. Optimal results were achieved with a laser power of 136 W, a printing speed of 300 mm/min and a powder mass-flow of 3.8 g/min. The used powder is a composition of separate nickel and iron powder particles. Therefore, the alloy must be formed inside the molten pool during the printing process. A successful FeNi44 print can be seen in figure 6. With the help of etching, the microstructure and the grain boundaries of the metal are made visible and the formation of the alloy is confirmed. The individual grains are larger than a single weld bead and hint at a successful amalgamation. The density of the printed specimen is above 99%. With these parameters a larger specimen was printed to conduct measurements of the thermal expansion factors at different temperatures.

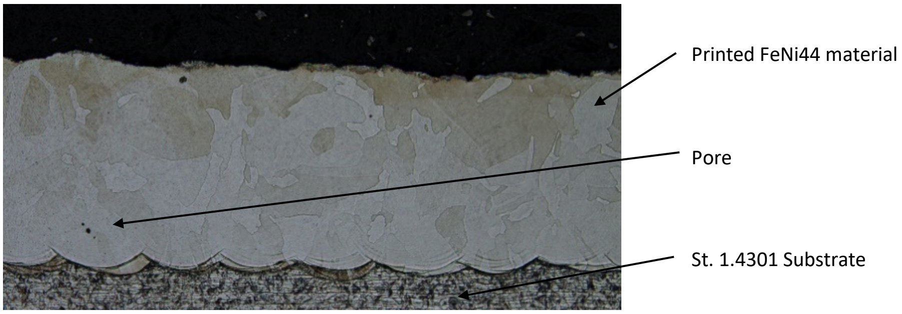

Fig. 6. Microsection of FeNi44 metal to a 1.4301 substrate.

A FeNi44 cuboid was built on top of a stainless steel substrate (see figure 7a). To measure the thermal expansion coefficient a cylindrical specimen was machined out of the printed body (see figure 7b). The specimen was then heated and the change in elongation evaluated. The calculated values were plotted alongside the expansion coefficient of a Nd:YAG crystal. The graph in figure 7c shows that the results are close to the crystal, but did not fully meet the expectations. This hints at higher percentage of nickel in the alloy due to segregation and vaporization of iron during the printing process. An EDX analysis confirms that the composition has changed to 49.2% nickel.

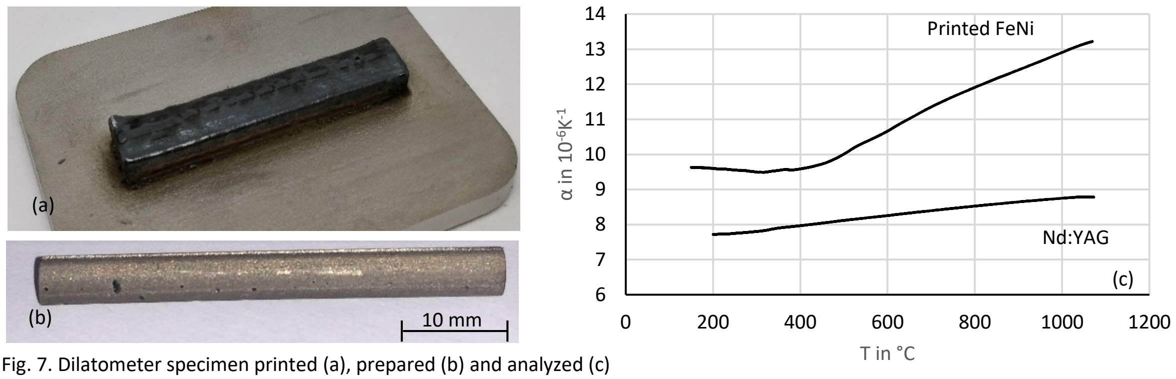

Fig. 7. Dilatometer specimen printed (a), prepared (b) and analyzed (c)

4. Conclusion

The results of the experiments carried out in this paper show that individual aspects for the combination of optical, thermal and structural properties with additive manufacturing are feasible. Especially the creation of a bond between Nd:YAG and nickel facilitates further research regarding multi-material components. The successful encapsulation of optical elements can lead to advancements in the manufacturing process by reducing the part count and consequently the amount of assembly steps needed.

The developed material composition consisting of iron and nickel shows a reduced thermal expansion and is an improvement compared to state-of-the-art copper crystal holders.

As an outlook, more complex and cooling optimized designs can be implemented. To reduce the thermal and mechanical stress introduced during the 3d printing process preheating is planned. This could obviate thermal cracks in the components by attenuating temperature gradients. Refinements of the material-system and a reduction of nickel by 5% to compensate the vaporization and segregation losses of the iron during the printing process will be made. An inclusion of molybdenum, titanium and copper could further improve the bonding and thermal properties.

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