ENHANCED MANUFACTURING POSSIBILITIES USING MULTI-MATERIALS IN LASER METAL DEPOSITION

Paper #1301

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Abstract

Additive Manufacturing (AM) addresses various benefits as the build-up of complex shaped parts, the possibility of functional integration, reduced lead times or the use of difficult machinable materials compared to conventional manufacturing possibilities. Beside these advantages, the use of more than one material in a component would strongly increase the field of applications in typical AM branches as energy, aerospace or medical technology.

By means of multi-material build-ups, cost-intensive alloys could be only used in high-loaded areas of the part, whereas the remaining part could be fabricated with cheaper compositions. The selection of combined materials strongly depends on the requested thermo-physical but also mechanical properties. Within this contribution, examples (e. g. used in the turbine business) show how alloys can be arranged to fit together, e. g. in terms of a well-chosen coefficient of thermal expansion (CTE).

As can be seen in nature, the multi-material usage can be characterized by sharp intersections from one material to the other (e. g. in case of a thin corrosion protection), but also by graded structures enabling a smoother material transition (e. g. in case of dissimilar materials which are joined together without defects). The latter is shown for an example from aerospace within this paper.

Another possibility is the simultaneous placement of several materials, e.g. hard carbide particles placed in a more ductile matrix composition. These particles can be varied in size (e.g. TiC vs. WC). Also the ratio between carbides and matrix alloy can be adjusted depending on its application.

Especially nozzle-based free form fabrication technologies, e.g. Laser Metal Deposition (LMD), enable the utilization of more than one material. Within this contribution, possibilities to feed more than one filler material are demonstrated. In addition, results of multi-material processes are shown. Finally, this work focuses on different (potential) applications, mainly in power generation but also for medical technology or wear resistant components.

Introduction

Laser Metal Deposition is already introduced in several industrial branches with the purpose of coating, part refurbishment but also the manufacturing of functional components. The process is suitable to a broad spectrum of materials (e.g. Fe-, Ni-, Co- or Ti-based alloys). Typical products are components for jet engines, turbines, tooling or medical implants.

Within this paper, the layer wise multi-material build-up by LMD with powder, process related challenges and compound characteristics are presented. To deposit material on a substrate the powder material is blown into the process zone by a nozzle, partially preheated in the laser beam and finally reabsorbed in the laser induced melt pool. Several different powder materials can be mixed in-situ by an integrated powder-mixing chamber in the nozzle tip (see Fig. 1). Due to a continuous as well as localized controlled powder mixing, LMD enables new possibilities in AM, e.g. deposition of composite materials as well as in-situ alloying without any additional joining process [1-6].

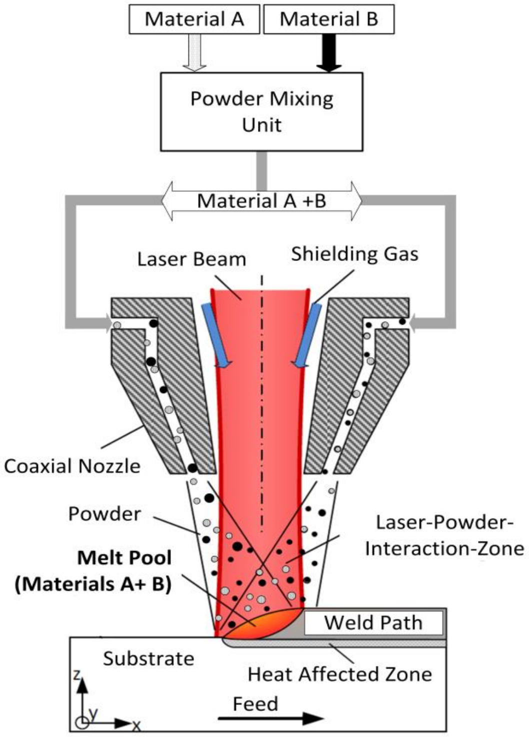

Fig. 1: Powder-based multi-material LMD processing

Hence, the LMD process enables additive manufactured parts with locally tailored properties. The use of integrated transition joints enables material combinations, which often cannot be joined conventionally.

Nevertheless, multi-material build-ups have to fulfil specific requirements in terms of porosity, mechanical properties, microstructure and possible failures (delamination, dilution or cracking). Within this paper, these characteristics are analyzed for several multi-material build-ups by using metallographic sections as well as EDX.

Possibilities of Multi-Material LMD

Nowadays, LMD is used for coating, refurbishing and manufacturing parts of well compatible material combinations. Furthermore, only one material is deposited in most cases. However, LMD using powder is suitable to mix different materials in-situ due to its unique characteristic. Hence, following multi-material configurations become possible:

I. locally tailored material properties,
II. integrated transition joints and
III. composite materials as well as
IV. in-situ alloying

Examples of mentioned multi-material combinations are shown within this paper

I. Locally Tailored Material Properties: Using LMD the filler material can be chosen according to the local requirements of the part, e.g. mechanical or thermal stresses. This can be achieved either by creating a sharp material intersection or by creating a graded material transition over several layers (see Fig. 2). This offers a “material follows function” approach in order to achieve a lighter and more efficient component design.

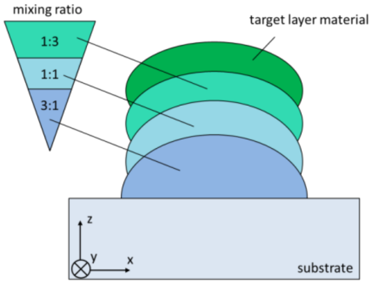

Fig. 2: Schematic illustration of a graded LMD transition **[7]**

II. Integrated Transition Joints: Buffer layers can be applied to overcome the metallurgical incompatibility. The buffer layer isolates the substrate material from the final build-up material and helps to evade brittle intermetallic phases or unfavorable differences in the thermo-physical properties. Creating a graded transition between the materials by tailoring the material concentration over several layers can reduce occurring stresses dramatically and improve the components tensile and fatigue properties [8]. Joining dissimilar metals is highly beneficial for several aerospace applications, e.g. multi-layer coatings for thruster nozzles.

III. Composite Materials: The mixing of metallic and non-metallic materials is an established approach to achieve custom-designed material properties. The integration of hard materials (e.g. carbides, ceramics) into a ductile metal matrix can significantly increase the wear resistance of the produced parts. This could be highly beneficial for several industrial applications, such as tool surfaces or turbine blade tips [1, 2].

IV. In-situ Alloying: The LMD process can also be used for an in-situ alloying approach. By controlling the mixture of different raw material powders the alloy composition can be customized simultaneously. Therefore, alloys with different mechanical and thermo-physical properties can be created simultaneously while processing.

Material Related Challenges

Several material combinations such as Ti-Fe or Cu-Al are highly interesting for industrial applications but cause several issues due to

I. differing thermo-physical properties,
II. poor miscibility,
III. differing absorptivity as well as
IV. inhomogeneous material distribution [9].

Hence, a fundamental understanding of process conditions, resulting material properties and potential failure mechanisms is essential for an industrial transfer of mentioned material combinations.

I. Differing Thermo-Physical Properties: Primarily the material properties thermal conductivity, melting range and CTE rise problems concerning the multi-material processing by means of LMD. Differing thermal conductivities and the change of heat conduction effected by the build height can affect the heat dissipation and therefore cooling rates [10]. The latter results in instable temperature conditions, which yield different, melt pool sizes and shapes as well as deposition rates. In order to counter this phenomenon, a local adaption of the deposition strategy and processing parameters can be applied. By using process-monitoring equipment, such as infrared cameras, CMOS cameras or pyrometers, the size of the induced melt pool and the local temperature field can be observed and controlled.

In order to achieve a metallurgical bonding between the processed materials, all elements need to be fully molten. A wide range of melting temperatures within a certain alloy may result in local material evaporation and therefore in a change of the chemical composition. Furthermore, some portions of the added material may not be molten caused by different melting temperatures. Hence, solid particles can ascend or descend in the melt pool which results in an inhomogeneous material distribution and/or unfavorable mechanical properties.

Due to the process immanent heat input, thermal expansion occurs (Fig. 3). While cooling, varying temperature states within the build-up and the substrate material induces local residual stresses. These may lead to unwanted formation of cracks or delamination as well as distortion. Using a graded material transition in order to create a steady stress gradient is a promising approach to overcome this issue.

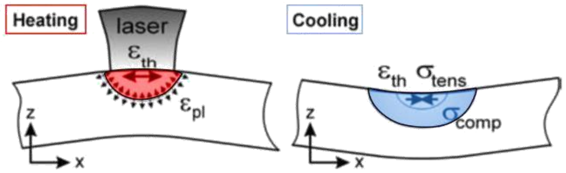

Fig. 3: Residual stress and strain due to local melt pool contraction [11]

II. Poor Miscibility: As mentioned, material combinations such as Fe-Ti or Cu-Al cause issues due to a decreasing miscibility during the cooling process. Once the maximum miscibility is reached, the formation of brittle intermetallic phases may occur (Fig. 4). These phases reduce the components tensile and fatigue properties dramatically. The metallurgical incompatibility can be overcome by using buffer layers with beneficial miscibility related to the substrate as well as the final build-up material.

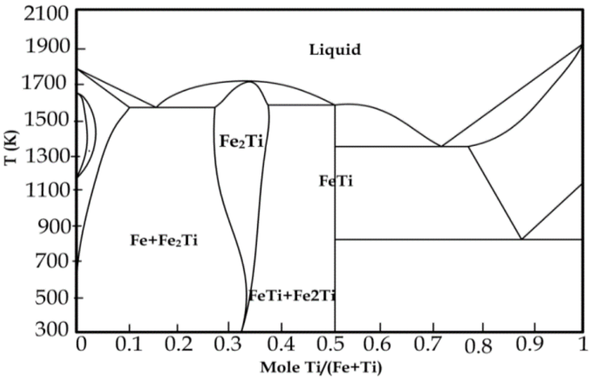

Fig. 4: Titanium-Iron binary phase diagram [9]

III. Differing Absorptivity: Materials often significantly vary in their electromagnetic absorption properties. The wavelength dependence of the absorption rate of different raw materials is shown in Fig. 5. By modifying the material composition during processing and, hence, the absorptivity, a changed energy input combined with locally differing temperature conditions might occur.

In case of combining stainless steel and copper, the absorptivity at typical laser wavelength of approx. 1064 nm (solid-state laser) might strongly vary. The major part of the radiation is reflected by copper and gets lost for the volume build-up. Additionally, the absorptivity is a function of the temperature: The absorptivity increases at higher temperatures in case of copper. The sudden temperature jump while melting leads to an overshooting and blow out of molten material [12].

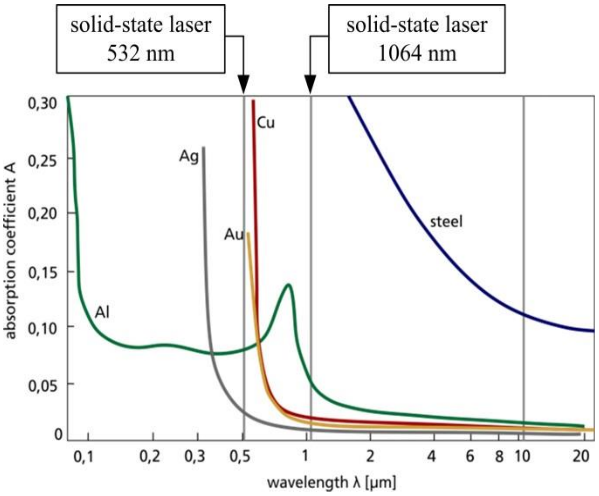

Fig. 5: Wavelength dependence of the absorption rate of different metals [13, 14]

In order to improve the absorption of highly reflective materials like copper, green lasers with favorable wavelength of λ=515 nm can be applied. The absorptivity of copper for green laser light is more than 10 times higher compared to infrared lasers [14].

IV. Inhomogeneous Material Distribution: Powder properties (e.g. particle size, particle form, surface condition) as well as laser-powder interaction are crucial for the process quality. Nevertheless, the used powder material must provide excellent flowing characteristics in order to achieve a constant and reproducible powder feeding.

To overcome material segregation of premixed powders, the material mixing has to be done closely to the process zone, which could be realized by using powder nozzles with a build in mixing chamber. Vaporization of single alloying elements can be avoided by well-chosen thermal boundary conditions or by well-adjusted filler materials.

In case of depositing hard particles into a metallic matrix, a homogenous distribution is requested in most cases. By means of gravity, hard particles might sink in case that the solidification of the melt is to slow. Hence, the process parameters have to be adjusted very well, especially regarding to the resulting melt pool temperature and movement.

Multi-Material Combinations with Beneficial Miscibility

A steady transition in material properties is desirable in order to decrease unwanted effects as high residual stress. Processing a material combination with good metallurgical compatibility and similar thermo-physical properties is a promising approach to achieve a smooth material transition. The presented work shows experimental investigations on a graded LMD transition based on the materials stainless steel AISI 316L and the nickel-based superalloy Inconel 718 (see Fig. 6).

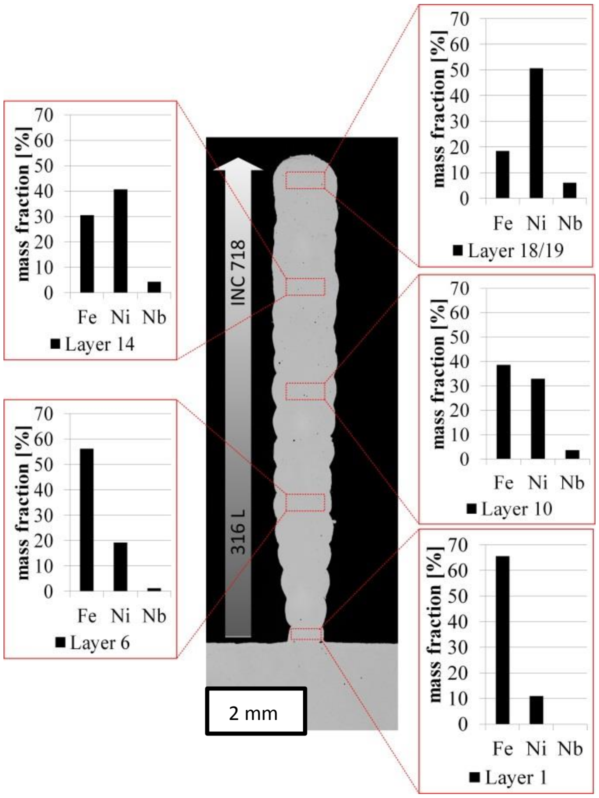

Fig. 6: EDX analysis (Fe, Ni, Nb) of the generated AISI 316L-INC718 graded material transition

Using a red laser (λ=1064 nm) with 1.7 mm spot size , power of 700 W and feed of 0,6 m/min two layers of stainless steel AISI 316L were deposited on a stainless steel 304L substrate. With increasing wall height the amount of AISI 316L powder material being fed was decreased and replaced with Inconel 718 powder material in order to gradually achieve a complete material transition from AISI 316L to Inconel 718. For analyzing the changing chemical composition an EDX analyses was conducted (see Fig. 6). Since Nb is only part of the alloy Inconel 718, it can be used as a marker element for detecting the gradual transition.

The EDX analysis was conducted at the layers 1, 6, 10, 14 and 19 to investigate the full material transition. It can be seen, that a dense volume with the chemical composition of stainless steel AISI 316L was generated in layer 1 (see Tab. 1). The EDX results prove that a linear growth of the Nb mass fraction could be achieved by linearly decreasing the feeding rate of AISI 316L and linearly increasing the feeding rate of Inconel 718.

Tab. 1: Chemical composition of the generated AISI 316L-Inconel 718 graded material transition (EDX)

Layer	Fe [%]	Ni [%]	Cr [%]	Mo [%]	Mn [%]	Nb [%]
Inconel 718	rest	50.0-55.0	17.0-21.0	2.8-3.3	0.35	4.7 - 5.5
19	18.4	50.6	19.7	3.8	0	6
14	30.6	40.7	19.5	3.3	0.4	4.4
10	38.7	32.9	19.3	3.6	0.7	3.6
6	56.1	19.2	18.8	3.1	1.1	1.2
1	65.5	11.0	18.9	2.6	1.4	0.0
AISI 316L	rest	10.0-13.0	17.5-19.5	2.0-2.5	0.0-2.0	0.0

This indicates a gradual replacement of AISI 316L and Inconel 718 in the same ratio (see Fig. 7). The EDX analysis of layer 19 shows, that AISI 316L has been fully replaced by Inconel 718 by the end of the desired material transition. The requested chemical composition can be precisely adjusted for each layer, because of the exact heat input by the laser and the resulting low dilution of previously placed material.

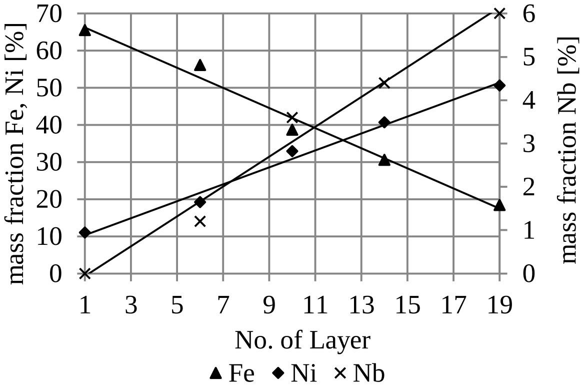

Fig. 7: Linear change of chemical composition with increasing number of layer

Moreover, the graded change of chemical composition shown by the EDX analysis clearly indicates an in-situ alloying process in each single layer. The micrograph of the graded transition zone (see Fig. 8) clearly shows that dense material with a very fine and homogeneous grain structure was generated.

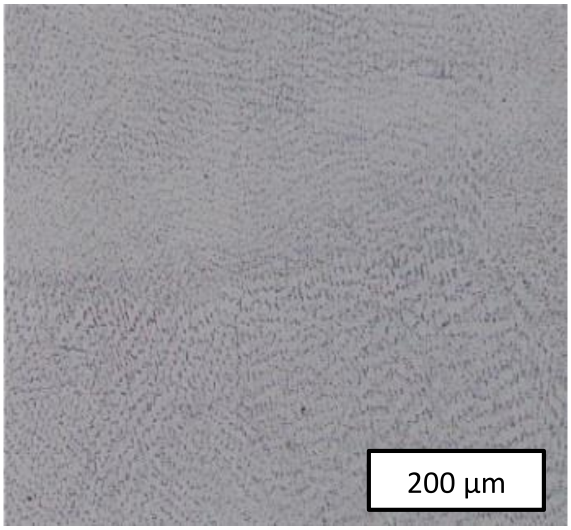

Fig. 8: Micrographs of the generated AISI 316L-INC718 material transition

Multi-Material Combinations with Limited Miscibility

The industrial demand for complex multi-material build ups is increasing. Dissimilar alloys are processed more and more to combine different material properties and gain flexibility. This approach often yields irregularities that negatively affect the strong metallurgical join between the chosen metals [15].

Copper on stainless steel is a potential material combination of high relevance. Stainless steel provides beneficial mechanical properties, but has poor electrical conduction properties. Copper provides beneficial electrical and thermal conductivity, but unfavorable mechanical properties [16]. This joint is particularly interesting for conductor tracks, heat exchangers, electrical components and coatings on thermal-loaded parts to improve heat dissipation.

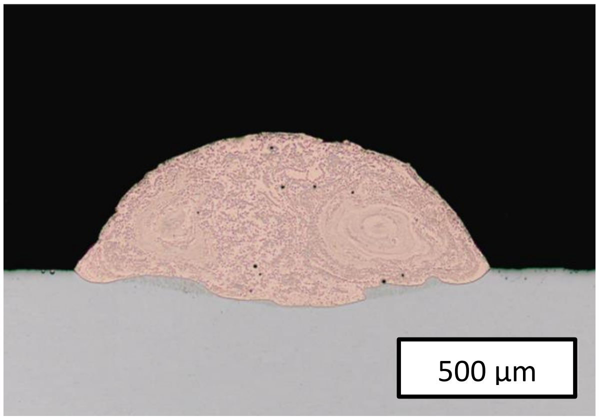

Fig. 9: Cross section of a single LMD track of Cu on AISI 304L

In this study 99.9% pure copper was deposited on an AISI 304L stainless steel substrate. The alloys were processed by Laser Metal Deposition using a green laser with a wavelength of 515nm and spot size of 1.2 mm. The operating parameters (laser power 500 W, feed 0.95 m/min) were optimized in order to obtain non-porous volumes and low penetration of the filler material (Fig. 9). The typical Marangoni-convection which is driven by thermally and/or concentration induced surface tension gradients is clearly visible. Caused by this convection molten steel globules were moved from the substrate into the copper. The microstructure of the single track is characterized by inhomogeneous distributed steel globules and star shaped dendrites in a copper-rich matrix (see Fig. 10a).

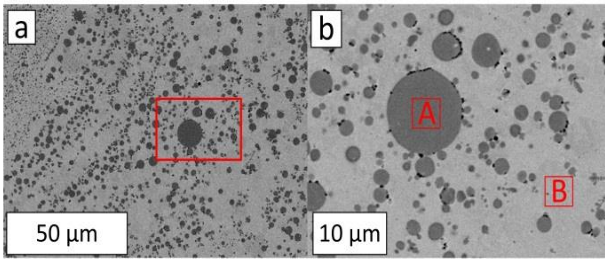

Fig. 10: SEM of the copper track
(a) view with lower magnification; (b) enhanced view of the red-indicated area in the left picture (a)

The composition of the dark spherical areas (A) measured by EDX (Fig. 10b) is similar to 304L stainless steel with some traces of copper and a minor nickel content (Fig. 11 left). The analysis of the bright zones (B) indicates a higher concentration of copper containing less iron and residual elements (Fig. 11 right).

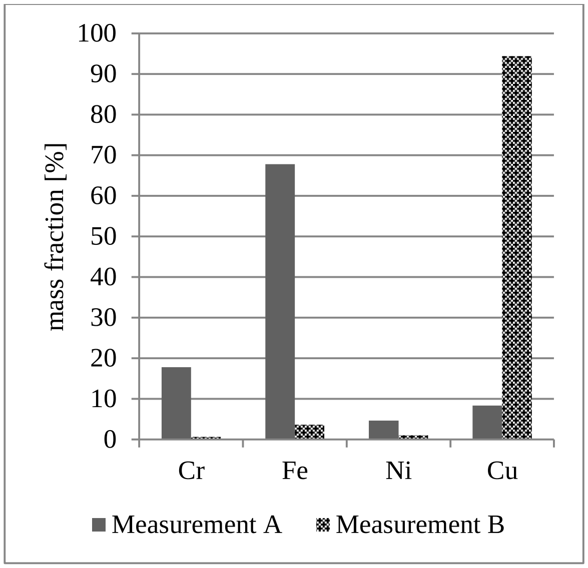

Fig. 11: EDX spectrum of zones A and B of Fig. 10b

The element mappings of chrome, iron and copper shown in Fig. 12 confirm the results of the EDX spectrum shown before.

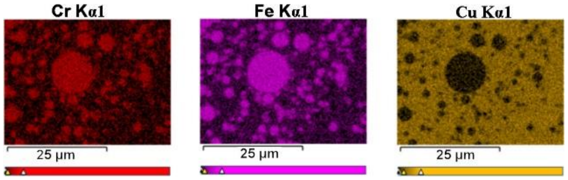

Fig. 12: EDX mapping of Fig. 10b

The results of the SEM study suits the binary phase diagram of iron and copper (see Fig. 13). Just two phases have been found in the investigated structure, due to the limited miscibility of copper and austenite. The molten material solidifies in an iron-rich and a copper-rich phase.

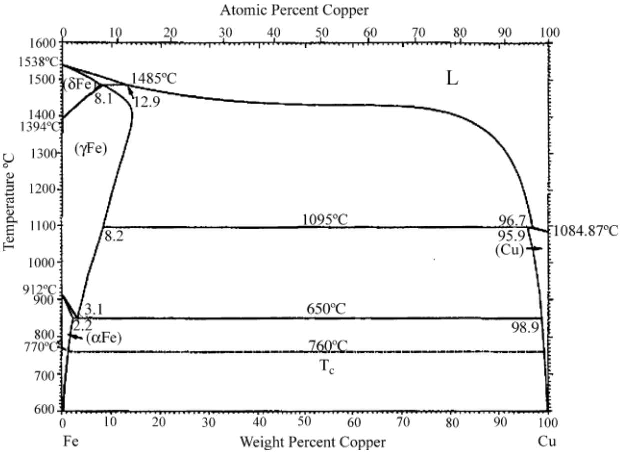

Fig. 13: Fe-Cu binary phase diagram [17]

Immiscible Material Combinations

Complete immiscibility is often caused by missing melting range overlap or missing liquid phase (thermic decomposition). Nevertheless, such combinations are applied for particle or fiber reinforced metal matrix composites (MMC) which provides highly beneficial mechanical properties (e.g. strength, wear resistance).

Such composites are typically made out of low-melting metal matrix, e.g. Ni (T_m=1455 °C) and NiBSi (T_m=940 °C), containing ceramic particles or fibers with a high melting temperature, e.g. TiC (T_m= 3140 °C) or WC (T_m= 2785 °C).

Especially the manufacturing of particle reinforced composites by conventional methods like casting is often difficult or even not possible. Novel approaches like self-propagating high-temperature synthesis (SHS), arc melting, liquid phase sintering, pressure less infiltration or Laser Metal Deposition enables new applications [18, 19].

For example TiC-Ni compound can be used in high-temperature structural applications, such as automotive, aerospace and a wide range of industrial operations related to cutting, rolling, pelletizing, stamping, punching, etc. [18].

Using LMD the matrix component is completely molten while the solid component is preheated and reabsorbed in the melt. Due to the melt pool convection (Marangoni effect) the particles are distributed and embedded homogenously.

The generated MMC TiC-Ni composite is characterized by a fine and homogeneous distribution of round TiC-particles in the Ni-matrix (see Fig. 14). The latter was adjusted by the individual feeding rates of hard particles and matrix material. Using the benefits of LMD even a graded distribution is possible. Due to the high bonding strength between the matrix material and reinforcing particles the specific stiffness, strength and fracture properties are increased significantly [18].

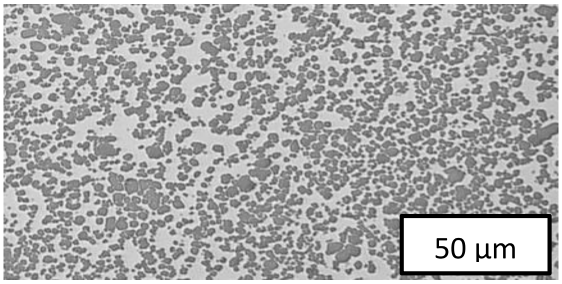

Fig. 14: TiC-Ni MMC-System

Compared to TiC-Ni the composite WC-NiBSi shows much coarser WC-particles with a bulkier shape (see Fig. 15). The latter could enhance the mechanical properties like tensile strength and ductility [20].

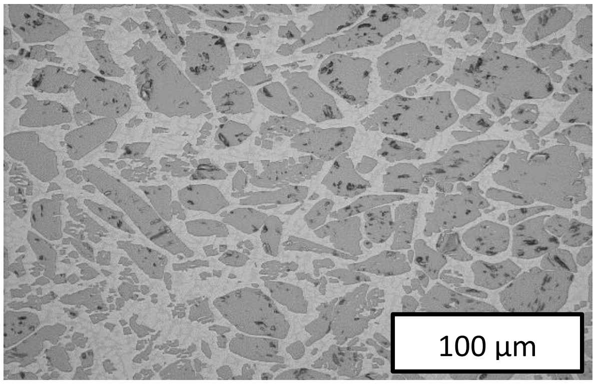

Fig. 15: WC-NiBSi-System

Conclusion and Outlook

Within this paper, relevant multi-material approaches to build up three-dimensional compounds using Laser Metal Deposition, related benefits and resulting challenges are shown. Hence, the paper gives an overview of possible material combinations obtained by LMD.

The LMD process can be successfully applied to process multi-material combinations with

- required and beneficial,
- limited or
- even no miscibility.

The investigations have shown that controlled linearly graded transitions between the beneficial miscible material combination SS AISI 316L and INC718 can be achieved by using LMD. Moreover, EDX analyses provided evidence of an in-situ alloying process along the transition zone.

Furthermore a detailed analysis of a LMD SS 304L and copper transition zone was conducted. Due to poor miscibility and severely different melting temperatures, the transition zone is characterized by a composite consisting of iron rich globules within a cooper rich matrix. Due to the limited miscibility little amounts of copper could be traced in the globules chemical composition. The globules distribution within the copper matrix results from the occurring Marangoni effect.

Additionally the combination of metallic materials and ceramics was investigated. On the one hand using Ni and TiC a very fine homogeneous distribution within the matrix was achieved. On the other hand using NiBSi and WC an also homogeneous but very coarse particle distribution was created, which affected the mechanical properties.

The broad range of material combinations, which can be processed by LMD, shows the enormous potential of this additive manufacturing approach. Investigations of further material combinations, such as Fe and Ti based alloys are expected to be highly beneficial for the improvement of industrial applications, especially in the aerospace and energy industries.

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Meet the Authors

Prof. Dr. Frank Brueckner studied automation and control engineering as well as business administration at the Technische Universität Dresden. He finished his PhD about theoretical aspects of laser cladding. Now he leads the business unit of Additive Manufacturing and Printing at the Fraunhofer IWS Dresden. Together with his team working at the Additive Manufacturing Center Dresden (AMCD), he mainly focuses on nozzle-and powder-bed based AM processes as well as printing technologies. In addition, he supervises PhD candidates at the Luleå University of Technology.

Mirko Riede studied mechatronics at the Technische Universität Dresden. In 2011 he finished his master thesis about high precision laser cladding at the Fraunhofer IWS Dresden. For the last 5 years he has been working on research projects related to additive manufacturing and structuring. He is now group leader of 3D Manufacturing at the Additive Manufacturing Center Dresden (AMCD) at Fraunhofer IWS.

Michael Müller studied aerospace engineering at the Technische Universität Dresden. In March 2017 he finished his diploma thesis about numerical simulations of the Selective Laser Melting process. His work at the Fraunhofer IWS focuses on theoretical and experimental investigations on powder bed processes

Franz Marquardt studied mechanical engineering with focus on construction at University of Applied Sciences Dresden. At the beginning of 2016 he finished his diploma thesis about the increase of the geometric resolution of laser wire cladding. Currently he is mainly focused on experimental projects related to wire and powder Laser Metal Deposition at the Fraunhofer IWS Dresden.

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