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# Metal matrix composites with ternary intermetallic inclusions fabricated by laser direct energy deposition

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ABSTRACT

At the present research, we obtained the metal matrix composites (MMC) of dispersion-reinforced nickel and titanium based alloys with variable content, structure and properties using laser direct energy deposition (LDED). We have ascertained that forming double and triple reinforced MexAly (x, y = 1.0.3) intermetallic structures with preset parameters of dispersibility and spatial distribution can be performed *in-situ*, using the LDED during the phase transformations of cooling and crystallization of the alloy. The preset gradients of final chemical composition, structure and microhardness have been obtained precisely by regulating the composition of the powder mixture supplied to the active zone of the LDED. We suggest a combination method of the LDED which can be an effective instrument for search and development of the new MMC and alloys for the additive manufacture field, as well as for studying structure- and phase-formation in the nonequilibrium conditions of laser synthesis.


## 1. Introduction

Development of metal matrix composites (MMC) on the base of nickel and titanium superalloys attracts more attention recently, for it is perspective for airspace industry. Of particular interest is a possibility of managing the MMC structure by embedding some reinforcing inclusions and/or alloys' grain microstructure refining which is being observed under high-speed cooling from a melt. So after the introduction of aluminum particles in the Ti or Ni alloy structure, conditions are formed for obtaining intermetallic phases i.e. aluminides of the corresponding metals, which combine high hardness, heat resistance and comparatively low density with high performance in the wear- and corrosion resistance.

Between the known composites of Ti, Ni and Al, the composite of $\alpha_2$-$Ti_3Al$ type, $\gamma$-TiAl (with $L1_0$ superstructure type), $\gamma'$-$Ni_3Al$ (with $L1_2$ superstructure type) and NiAl (with $B_2$ superstructure type) [1,2] are considered to be the most perspective for their properties' combination. Besides $Ni_3Al$ intermetallic phase is noted for the anomalous dependence of yield strength on the heating temperature. With the temperature growing the yield strength of the $Ni_3Al$ aluminide does not decrease, as for the majority of metals and alloys, but increases, which is of exceptional value at tools' fabrication, intended for functioning in elevated temperature conditions.

Two-phase intermetallic phases of $(\alpha_2 + \gamma)$-$Ti_xAl$ type, including the ternary nickel-alloyed ones, also draw attention as constructional materials for airspace manufacturing. Because of the dissolution and precipitation effects, Ni-Ti-Al ternary systems have better mechanical properties under high temperatures than binary Ni-Ti systems [3]. Moreover, the papers [4,5] reported that multilayer Ni-Ti-Al coatings have better anticorrosion properties than the Ni-Ti system due to the Al passivation film on their surface. The study [6] pointed out that adding Ti leads to improvement of mechanical properties of the NiAl alloys under high temperatures. It was also demonstrated that adding Ti to the NiAl alloys provides significant creep strengthening through separation of the Heusler phase $Ni_2AlTi$ ($\beta'$) [7]. Of ternary intermetallic systems it is necessary to notice $\gamma$-$Ni_3$(Al,Ti) (Heusler phase with $L2_1$-structure), which is extremely perspective for propulsion engineering [8]. According to the [9–11] studies, Ni-Ti-Al system are a potential alternative of Ni-Ti and Ni-Al in aerospace, turbine, automobile and biomedical applications. Wang et al. [12] revealed that laser cladded Ni-Ti-Al demonstrates high hardness, wear and corrosion resistance due to Al concentration growth.

Ternary alloys on the Ni-Cr-Al base alloyed by niobium, tantalum or/and yttrium are also of interest for the aircraft engine building [13,14]. Ni based supperalloys are widely used in gas-turbine engines because of their good mechanical properties and excellent

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erosive and corrosive resistance [15,16]. To raise the effectivity of the gas-turbine engines and obtain a higher traction-weight relation (TWR) a higher temperature is needed. One of the ways to solve this problem is using heat-resistant coating, which usually consist of upper ceramic layer and bottom metallic binder. MeCrAlY type alloys (where Me = Ni, Co and NiCo allow limiting oxidation and decreasing discrepancy between the ceramic layer and the Ni superalloy based bottom matrix [17–27]. Regulating structure of MeCrAlY coatings is also an important task; it can be solved by increasing Al concentration, inclusion of second phase $Al_2O_3$ particles and/or adding elements like Re, Si and Ti [10,11,19,24,25,28].

Previously additive technologies (DMD, LENS, 3D laser cladding, EBM) have been used with prepared the MMC powders of constant composition [1–3,16,19,20,28]. A three-dimensional combinatory metallurgic method named as *'rapid prototyping of alloys'* have recently been proposed [2,19,29], and had a successful approbation in TWIP-steels with lowered density, high-entropy alloys, intermetallic alloys, as well as high-strength martensite and high-module steels. The authors of the current study have earlier suggested using this method in additive technologies (3D laser cladding and selective laser melting – SLM) for *in-situ* constructing microstructures and regulating properties of functional graded structures in situ in Ti-Al, Ni-Al, Ti-Ni-Al, Ti-Fe, Fe-Al, NiCr-Ti, NiCr-Al intermetallic systems. A laser assisted MMC fabrication based on Ni and/or Ti reinforcement by $Me_xAl_y$ (where Me = Ni and/or Ti based alloy; x, y = 1...3) could be realized as *in-situ* $Me_xAl_y$ intermetallic synthesis directly in the matrix of the basic material [1,2,19,28,30–32].

Though structure formation kinetics [33–41], especially in the ternary systems under intensive laser influence (LI) demands clarification. Technology of functional gradient structures (FGS) and composites (FGC) making was described long ago [1,2,31], and ability to control the mechanical properties of the FGC during the 3D laser cladding was also shown [1,32]. But developing the gradient MMC requires a significant amount of knowledge in phase transformations to avoid composites where brittle or metastable intermetallic phases could be formed.

The aim of this study was to demonstrate the feasibility of laser direct energy deposition (LDED) process for fabrication of the MMC reinforced by intermetallic $Me_xAl_y$ phases and the FGC-structures from a mixture of titanium and/or nickel based alloys and alternating from layer-to-layer aluminum powder. In the present study, we compared different types of the MMC and the FGC by microstructures, phase content, structure formation kinetics and microhardness. The microstructure and chemical composition were characterized based on the optical and SEM equipped EDX microanalysis, microhardness testing, and XRD in order to understand the process mechanism.

## 2. Materials and experimental procedure

### 2.1. Powder materials

The following powders were used in the experiments by $Me_xAl_y$ intermetallic synthesis. The aluminum powder had 99 wt% of Al. The titanium powder was TiGd2 grade 99.76 wt% Ti. Both powders are produced by the TLS Technik GmbH&Co, Germany. The NiCr super alloy Inconel 625 (Sulzer Metco Co.) was used as Ni powder, which had the following chemical composition: Cr – 21.5, Fe – 2.5, Mo – 9, Nb 3.7 wt%, bal. – Ni. At last, the nitinol powder was produced by the TLS Technik GmbH&Co also and contained 99.76 wt% of intermetallic NiTi phase. The NiTi powder was represented by a 60 μm fraction. The NiTi stoichiometric ratio was 45 wt% of Ti and 55 wt% of Ni. The Al, Ti, NiTi and NiCr powder particles were mainly spherical with the size of ~80–120 μm for 95% of them. The powder size distribution was studied by means of a granulomorphometer ALPAGA 500NANO (OCCHIO s.a.).

The substrates were round plates with the 65 mm diameter and 5 mm height made of Ti-6Al-4V for titanium matrix composite and 12X18H10T stainless steel substrates for Ni based matrix composites. The 3D samples produced in the plane measured 40 × 40 mm.

### 2.2. Experimental setup for the LDED

All the experiments were carried out using a HAAS 2006D (Nd:YAG, 4000 W, cw) with the laser beam delivery system, powder feeding system, coaxial nozzle, and numerically controlled 5-axis table. Main features of the equipment were reported earlier [2,19]. It is important to emphasize that the two-channel powder feeder of the LDED setup is an efficient instrument for the management of powder mixture contained in a Me + Al system because of controlling the flow rate of argon, which is also feeding and protective gas. The first channel of the feeder with the Me powder had a gas flow rate of approximately 20 L/min while the second one with the Al powder was ~10 L/min and could be changed during the experiment. The accuracy of the position control system was $\sim 30 * 10^{-6}$ m. The variable parameters were the LI parameters – power *P*(W), scanning velocity *V*(m/s), and the powder feed rate $G(kg/s^{-1})$. The constant parameters were the diameter of the laser beam on the substrate, $d = 3 * 10^{-4}$ m. Hatching distance was equal to laser beam diameter, layer thickness was ~0.2 mm.

### 2.3. Scheme of functional and gradient MMC

The method of the functional and gradient MMC fabrication used in the present study is schematically presented in Fig. 1. The powder feeding rate was ~0.3–6 g/min for Ti-Al system; 0.8–15 g/min for the NiCr-Al system and 10–25 g/min for the NiTi-Al system. The layers were made of Me = (Ti, NiCr or NiTi) and Al powders on a related substrate by the following strategy: the first two layers consisted of 90% Me + 10% Al, the next two layers were of 70% Me + 30% Al, the third couple of 50% Me + 50% Al and the upper 7th and 8th layers had the ratio of 30% of Me + 70% of Al. Each second layer was formed on the bottom layer after turning it around 90 degrees. The laser scanning speed *V* was changed from 200–500 mm/min and laser power *P* = 800–1000 W.

Since the LI is reflected well by aluminum, the more refractory Me (Ti, NiCr or NiTi) must be the matrix material, and in

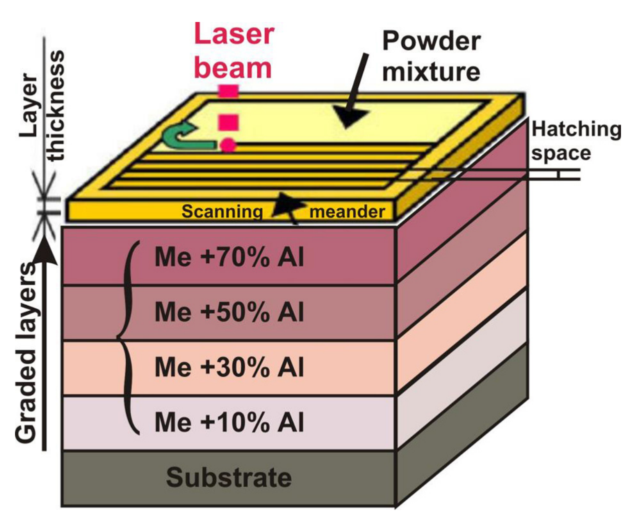


**Fig. 1.** Schematic of the multi component graded structure fabrication by 3D laser cladding. Longitudinal – L; transversal – T.