Structure Formation in Ni Superalloys During High-Speed Direct Laser Deposition

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Abstract. Additive technologies are replacing the conventional methods of casting and subsequent time-consuming machining because of its high productivity. Recent engineering development in the field of additive manufacturing allows increasing assortment of useful powder materials. Technology of high-speed direct laser deposition (HSDLD) is a one of most perspective new technologies. It allows realizing heterophase process during the manufacturing, which there is process of partial melting of used powder is realized. The product is formed from a metal powder, which is supplied by compressed gas-powder jet directly into the laser action zone, wherein the jet can be as coaxial and as non-coaxial.

Ni-based alloys found their application in many industrial areas, mostly there are used engine systems, aircraft and shipbuilding, aeronautics. The unique combination of operational characteristics depending on the type of alloy makes them promising materials. Heating and cooling rates during direct laser deposition determine structure and affect on its properties. Research is focused on structure and phase formation within technological process of HSDLD for Ni-base superalloys. Mechanical tests were carried out on the static tensile test, microhardness was measured. Based on research results the high-speed direct laser deposition technology could be used for manufacturing of products from different Ni-based alloys without subsequent heat treatment.

Introduction

Additive manufacturing could replace traditional methods of preparation of products: casting and subsequent mechanical treatment, because of its economy of raw and expensive materials and human resources [1-4]. On of the most perspective technology of products manufacturing is high-speed direct laser deposition (HSDLD) when the product is formed from a powder, which is supplied by compressed gas-powder jet directly into the laser action zone [5,6]. Development of additive technologies allows to work with different types of alloys, including Nickel, titanium, iron and cobalt base alloys [7,8].

Nickel base superalloys found their application in many industrial areas: shipbuilding, aerospace, power-plant engineering. Some applications: aircraft ducting systems, engine exhaust systems, thrust-reverser systems, working and nozzle blades, turbine rotor disks, fuel and hydraulic line tubing, spray bars, bellows, turbine shroud rings, and heat-exchanger tubing in environmental control systems and etc. Depending on the alloying elements in nickel alloys various types of hardening will occur.

Results of theoretical and experimental investigations of high-speed direct laser deposition from powder materials are presented in latest works [6,9]. In this paper authors presented results of structure formation during high-speed direct laser deposition on the alloy with solid solution hardening and carbide precipitation - Inconel 625 (Ni-Cr-Mo-Nb) and on the experimental alloy with gamma prime phase hardening and carbide precipitation– alloy (Ni-Co-Cr-Al-Ti-Nb-Mo-W). Based on experimental results, products made by direct laser deposition without further isostatic pressing, or heat treatment, have a properties at the level of rolled metal and higher.
Materials and research methodic

Experimental studies of deposition processes were carried out at the Institute of Laser and Welding Technologies SPbPU (ILWT) using experimental set-up based on 5kW IPG fiber laser YLS-5000, 5D CNC machine, Sultzer Metco Twin 10-C powder feeder and HighYAG BIMO processing head (Figure 1).

During experiments of DMD laser power were ranged 0,5-1,5 kW. Gas-powder jet studied separately at another experimental set-up, equipped with high-speed monochrome camera Citius Centurino C100, high-resolution monochrome camera Basler acA-2000gm, lightening device based on 20W 808nm diode laser and laser line generator. Experiment automation was done in LabVIEW 2012 programming environment. Side and coaxial nozzles of different design formed gas powder jets. Powder alloys Inconel 625 (Ni-Cr-Mo-Nb) and experimental alloy (Ni-Co-Cr-Mo-W-Al-Ti-Nb) were used. Fractional composition of 53-150 microns, the shape of the particles is spherical. Metallographic studies were carried out on microscope DMI 5000 (Leica) with Tixomet software. Researches of chemical composition and chemical elements distribution were made on scanning electron microscope Phenom ProX and Mira Tescan microscope using console Oxford INCA Wave 500. To determine the mechanical properties samples were tested on uniaxial tension, using universal testing machine Zwick/Roell Z250 Allround. Microhardness of produced samples was determined using Hardness tester Buehler Micromet 5103.

Experimental results

As a result of complex experimental research [6,10] samples of different geometry were prepared using coaxial nozzle and side nozzle. Different types of samples are presented on fig.2. Good results in technological experiments also get for other materials: austenitic steels, stellites (Co-based alloys), cermets with WC particles, titanium alloys. Investigations of macrostructure of samples from alloy Inconel 625 have a good density – porosity less than 0,05 vol.%, no gas pores and cracks. For experimental alloy special regime of sample preparation was designed to exclude intensive cooling and heating during HSDLD.
Fig.2. Samples are produced using high-speed direct laser deposition (b,c).

The microstructure of samples (alloy Inconel 625), prepared using different power of laser, mostly have cast condition. At the lower power less than 1 kW it can be seen non melted parts of powders. Gray region is nickel-based gamma solid solution, white grid along the grain boundaries - niobium and molybdenum carbides, black dots is a finely dispersed silica, alumina and manganese oxide. Microstructure of Inconel 625 polished sample and fracture are presented on fig.3. Photographs show large amount of facets with traces of plastic deformation, which indicated viscous failure for both types of samples. Mechanical characteristics are presented in Table 1.

Fig.3. Microstructure of samples from Inconel 625 (Initial (a,c) and heatreated (b,d) condition).
Table 1. Mechanical properties of samples prepared from Inconel 625 alloy.

<table>
<thead>
<tr>
<th>Condition</th>
<th>$\sigma_{0.2}$, MPa</th>
<th>$\sigma_{b}$, MPa</th>
<th>$\delta$, %</th>
<th>HV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial condition (after HSDLD)</td>
<td>488</td>
<td>865</td>
<td>28.8</td>
<td>220</td>
</tr>
<tr>
<td>HSDLD + heatreatment (T=1000 C, 3 h)</td>
<td>475</td>
<td>855</td>
<td>22.3</td>
<td>210</td>
</tr>
<tr>
<td>Rolled metal</td>
<td>414-758</td>
<td>827-1103</td>
<td>30-60</td>
<td>175-240</td>
</tr>
<tr>
<td>Cast metal</td>
<td>310</td>
<td>590</td>
<td>25</td>
<td>195</td>
</tr>
</tbody>
</table>

Experimental Nickel base alloy (Ni-Co-Cr-Mo-W-Al-Ti-Nb) was prepared by two methods for comparing: casting and HSDLD. On fig.4 microstructure and fracture are presented in cast and deposition condition.

![Fig.4](image1)

The structure of the samples obtained by HSDLD significantly more disperse than samples in cast condition, which provides the potential for a high level of mechanical properties. Same results for fracture: HSDLD sample is characterized by ductile failure; sample in cast condition has brittle failure. Microstructure of both samples are characterized gamma and gamma prime phases, carbide precipitations. The alloy there is a high content of nickel, cobalt and chromium, forming the gamma matrix. The uniform distribution of aluminum and titanium in the alloy, suggests the presence of to 50% gamma prime phase in solid solution. Also EDX analysis show small amount of titanium, niobium and molybdenum carbides.
Table 2. Mechanical properties of samples prepared from experimental alloy (system Ni-Co-Cr-Mo-W-Al-Ti-Nb).

<table>
<thead>
<tr>
<th>Condition</th>
<th>$\sigma_{0.2}$, MPa</th>
<th>$\sigma_{b}$, MPa</th>
<th>$\delta$, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial condition (after HSDLD)</td>
<td>1046</td>
<td>1353</td>
<td>11.5</td>
</tr>
<tr>
<td>HSDLD + heatreatment (HIP)</td>
<td>820</td>
<td>985</td>
<td>7.4</td>
</tr>
<tr>
<td>Cast metal</td>
<td>1075</td>
<td>1108</td>
<td>2.9</td>
</tr>
</tbody>
</table>

The tensile strength of a HSDLD samples show increasing on 22% and elongation 2.9 times higher in comparing with cast samples. Because of ultrafine structure gamma prime phase in deposited samples formed in nanoscale dimension. Such formation of intermetallic $\text{Ni}_3(\text{Al,Ti})$ in solid solution positively affect to the mechanical characteristics of the produced samples and causes them to rise. On fig.5, gamma prime phase in different samples is presented. In HSDLD sample gamma prime phase much less in comparing with cast sample.

Fig.5. Gamma prime phase in samples a – cast condition, b – deposited condition.

Conclusions

High-speed direct laser deposition technology allows producing quality products with good mechanical properties on the level of rolled metal or higher. Structure of produced samples has a heterophasic character. The research results showed, that developed high-speed direct laser deposition technology can replace the currently used technologies, providing multiple increase productivity and material savings, in spite of its technological complexity.

This technology could be used for different types of Ni base alloys including high doped alloys like Rene 41, 95, N5, N6. Microstructure is ultrafine, size of carbides less than 1 µm, size of $\text{Ni}_3(\text{Al,Ti})$ coherent intermetallic in nanoscale range. Mechanical characteristics a half times higher than the characteristics of the cast condition (for casting alloys) and are arranged on the level of rolled metal (for wrought alloys).
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References


