Journal of Materials Processing Technology 229 (2016) 484–491

Contents lists available at ScienceDirect

Journal of Materials Processing Technology

journal homepage: www.elsevier.com/locate/jmatprotec

Processability of different IN738LC powder batches by selective laser melting

Roman Engeli[a,b,*], Thomas Etter[a], Simone Hövel[a], Konrad Wegener[b]

[a] ALSTOM (Switzerland) Ltd., Brown-Boveri-Strasse 7, 5400 Baden, Switzerland
[b] Institute of Machine Tools and Manufacturing (IWF), ETH Zürich, Leonhardstrasse 21, 8092 Zürich, Switzerland

ARTICLE INFO

Article history:
Received 3 July 2015
Received in revised form 5 September 2015
Accepted 28 September 2015
Available online 3 October 2015

Keywords:
Selective laser melting (SLM)
IN738LC
Nickel-base superalloys
Powder
Hot-cracking
Chemical composition

ABSTRACT

Selective laser melting of high γ' strengthened superalloys such as IN738LC is of huge interest for stationary gas turbine applications. In order to identify the influence of the powder characteristics on SLM processing, several batches of commercially available IN738LC powder made by gas and water atomization were characterized with respect to particle size distribution, morphology and chemical composition. The different powders were processed under equal conditions by selective laser melting (SLM) and the build quality was assessed by quantitative image analysis. Samples made out of the water atomized (WA) powder showed a higher porosity after SLM compared to the spherical gas atomized (GA) powders due to the greater irregular morphology of the powder. The porosity of the gas atomized powder batches was found to be influenced by the flow behavior of the powder. Large differences were observed for the hot cracking susceptibility of the different powder batches during SLM processing. The cracking density was correlated to the chemical composition and it was found that the minor element Si has a large influence on the SLM processability of the IN738LC powder. A strict control of this element is important to decrease the hot cracking tendency and extends the SLM processing window of this alloy.

1. Introduction

Additive manufacturing (AM) methods have recently gained a lot of attraction in industry due to their huge potential with regard to design freedom, individualization, life cycle cost reduction and process chain simplification. The technology originated as a method of rapid prototyping and is now maturing into a manufacturing method for production of fully functional components. One of these emerging AM methods is selective laser melting (SLM) which allows the production of complex parts out of metal powder. Introduced by Meiners (1999), the process consists of a repeated application of a thin (20–60 μm) metal powder layer which is selectively melted by a scanning laser beam according to the layer information from a sliced CAD model. Layer by layer, the final part is consolidated into a fully dense, functional component. The resulting material is very homogenous with regard to the chemical composition and almost free of segregations due to the small melt pool size and the fast cooling rate characteristic for the process.

The efficiency of aero- and stationary gas turbines is limited by the service temperature at which the engine can be operated. Being limited by the high temperature properties of the applied materials and its coatings, sophisticated cooling schemes such as film cooling were developed to further increase the efficiency of the engines. This strategy is however limited by the capabilities of classical manufacturing methods like investment casting or machining. The former is prone to a large amount of scrap and rejects. In the latter case, it is furthermore not uncommon to remove up to 90% of the input volume resulting in huge waste of material, energy and time. The SLM technology not only allows the fabrication of highly complex parts but has the potential to further improve the performance of components by using improved cooling schemes. Furthermore, it can also considerably decrease life cycle cost and simplify the process chain. For these reasons, SLM is increasingly applied in the aero- and stationary gas turbine business for the fabrication of and repair of hot gas path components as reported by Robb (2015).

Nickel-base superalloys are commonly applied in the hot gas path of aero and stationary gas turbines due to their outstanding high temperature strength and oxidation resistance. The high temperature strength of these alloy class is based upon the solid solution strengthening (Cr, Co, Mo, W, Ta) of the fcc γ-Ni matrix

* Corresponding author.
E-mail address: roman.engeli@power.alstom.com (R. Engeli).

http://dx.doi.org/10.1016/j.jmatprotec.2015.09.046
0924-0136/

Table 1
Main and residual elements content of the eight analyzed powder batches. The first two rows show the min./max. values for the cast version of this alloy according to the technical datasheet Alloy IN-738 Technical Data (1981).

	Main alloying elements [wt%]												Residual elements [wt%]		
	Ni	Cr[a]	Co[a]	Mo[a]	W[a]	Ta[a]	Al[a]	Ti[a]	Nb	C	B	Zr	Si	Fe	Cu
Min.	Balance	15.7	8.0	1.5	2.4	1.5	3.2	3.2	0.6	0.09	0.007	0.02	–	–	–
Max.		16.3	9.0	2.0	2.8	2.0	3.7	3.7	1.1	0.13	0.012	0.08	0.3	0.05	–
A		15.8	8.6	1.7	2.6	1.7	3.5	3.3	0.80	0.096	0.011	0.060	0.085	0.06	0.011
B		16.1	8.5	1.7	2.6	1.8	3.5	3.4	0.85	0.097	0.010	0.065	0.064	0.08	0.012
C		16.1	8.8	1.8	2.4	2.9	3.5	3.5	0.75	0.130	0.012	0.652	0.105	0.11	0.611
D		15.9	8.4	1.8	2.6	2.0	3.4	3.5	0.80	0.110	0.013	0.041	0.030	0.06	0.164
E		16.2	8.6	1.8	2.7	1.7	3.5	3.3	0.80	0.140	0.015	0.023	0.034	0.82	0.099
F		16.1	8.4	1.7	2.7	1.7	3.5	3.7	0.80	0.140	0.012	0.056	0.212	0.13	0.004
G		16.0	8.6	1.6	2.8	1.8	3.5	3.4	0.90	0.120	0.009	0.011	0.026	0.15	0.001
H		15.9	8.3	1.8	2.6	1.9	3.5	3.3	0.80	0.096	0.014	0.032	0.018	0.09	0.004

[a] values according the suppliers material certificate.

and on precipitation hardening by ordered, coherent intermetallic phases such as γ′-Ni_3(Al,Ti) or γ″-Ni_3Nb. These phases are extremely stable and show only a very low driving force for coarsening due to their low lattice mismatch. Additional strengthening is provided by solid-solution strengthening of the ordered γ′ phase by Ta, Ti and Nb and by grain boundary strengthening with carbides, borides, zirconium and boron. Up to 12 or more functional elements are therefore typically present in commercial superalloys.

Processing of these Ni based superalloys by SLM has mainly focused on solid solution hardened superalloys and the γ″-strengthened alloy IN718. These alloys are all considered to be "easy to weld", as defined by Prager and Shira (1968) due to their low content of the γ′ forming elements Al + Ti. For high load applications, superalloys with higher γ′ volume fraction are required. This class of alloys is inherently more difficult to process and tends to form severe hot cracks during SLM processing at room temperature as shown by Carter et al. (2012) for the alloy CM247LC.

Even though IN738LC is reported by Ojo et al. (2004a) to be sensitive to liquation cracking, it has been successfully processed by SLM with a high density and very little micro-cracking by Rickenbacher (2012). This alloy has shown promising high temperature properties in first investigations by Rickenbacher et al. (2013) and is therefore a primary candidate of high γ′ fraction superalloys to be implemented in serial production. In addition, Kunze et al. (2015) recently found that SLM processed IN738LC not only shows a preferred crystallographic orientation along the build-up direction but also along the scan direction of the laser beam. Such an anisotropic behavior can be interesting to optimize the microstructure according to local load conditions in a component.

The choice and definition of suitable raw materials becomes increasingly important when maturing SLM away from the usual research or prototyping production towards a more serial production purpose. Being a young technology, not much investigation has yet been done with regard of influence of the powder characteristics on the processability with SLM. Several standards are available for properties like particle size distribution, flow properties and powder densities, but there is no consensus about their applicability to powders for SLM. Insufficient standardization is yet available for several other parameters such as morphology, thermal properties and chemical composition, as pointed out by Cooke and Slotwinski (2012). Gu et al. (2014) compared the SLM processing behavior of three Ti6Al4V powder batches and found that different processing conditions are required due to changes in the thermal conductivity of the powder bed. Similarly, Spierings and Levy (2009) showed that different powder batches of stainless steel 316L can have slightly different processing windows. With respect to chemistry, Tomus et al. (2013) found for Hastelloy X that the amount of Si and Mn influences the hot cracking susceptibility during SLM. No information however is given in that publication about the critical element range. In the present work, the influence of different commercially available IN738LC powder batches on the resulting part quality after processing under equal condition was investigated.

2. Materials and methods

Eight different batches of IN738LC alloy powder with the nominal composition of 16% Cr, 8.50% Co, 1.7% Mo, 2.6% W, 1.7% Ta, 0.9% Nb, 3.4% Al, 3.4% Ti, 0.11% C, 0.01% B, 0.05% Zr, Ni (balance) were obtained from five different suppliers. For simplicity, the batches were designated with letters from A to H. All powders were gas atomized (GA) using argon as atomization gas, with the exception of batch F which was water atomized (WA). Powder batches D, E and H were atomized from vacuum molten feedstock material (VMF), whereas batch C was directly alloyed from the elemental raw materials. No information about the feedstock material was available for powders A, B, F and G.

Each powder batch was characterized in terms of chemical composition, particle size distribution (PSD) and morphology. The chemical composition of the eight batches is reported in Tables 1 and 2. For elements with a nominal content >1 wt%, the chemical composition as provided by the supplier's material certificate is reported. The content of the other elements < 1 wt% was determined by ICP-MS according ISO 17294 and for C, S, O and N by combustion analysis according ASTM E1019 by the RMS Foundation (Bettlach, Switzerland). The particle size distribution was determined by laser diffraction using an Analysette22 Microtec Plus with wet dispersion unit from Fritsch GmbH (Idar-Oberstein, Germany) and applying the Fraunhofer approximation. The measurement was performed using tap water as a dispersion medium. Three separate PSD measurements were done per batch and the average is reported. The apparent density of the powder batches was measured according ASTM B329-14 using a Scott volumeter and the tapped density was measured according ASTM B527-14. To assess the flowability, the Hausner ratio, defined as the ratio between the tapped and apparent density, was determined from these values. As pointed out by Grey and Beddow (1969), the Hausner ratio relates to the friction conditions in a moving powder and therefore, a low Hausner ratio is an indication for good flowability.

A M2 LaserCusing SLM machine from Concept Laser GmbH made available through inspire AG, Zürich (Switzerland) was used for SLM processing. It is equipped with a Nd:YAG solid state laser from Rofin-Sinar Laser GmbH and provides a continuous laser beam with a wavelength of 1070 nm and a spot size of 0.09 mm. All batches were processed under equal conditions using process parameters for 30 μm layer thickness previously developed by a project funded by the Swiss commission for technology and innovation (CTI project