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Procedia Manufacturing 10 (2017) 771 – 778

Procedia MANUFACTURING

45th SME North American Manufacturing Research Conference, NAMRC 45, LA, USA

Ultrasonic Vibration-Assisted Laser Engineered Net Shaping of Inconel 718 Parts: A Feasibility Study

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Abstract

Laser engineered net shaping (LENS) has been applied as a key technology in direct manufacturing or repairing of high added-value metal parts. Recently, many investigations on LENS manufacturing of Inconel 718 parts have been conducted for potential applications of the aircraft turbine component manufacturing or repairing. However, fabrication defects such as pores, cavities, and heterogeneous microstructures always exist in the parts, affecting part qualities and mechanical properties. Therefore, it is crucial to LENS-manufacture Inconel 718 parts in a high-quality and high-efficiency way. Ultrasonic vibration has been introduced into various melting metal solidification processes for process improvements. However, there are no reported investigations on ultrasonic vibration-assisted (UV-A) LENS of Inconel 718 parts. In this paper, for the first time, UV-A LENS is proposed to reduce the fabrication defects of Inconel 718 parts. The experimental investigation is conducted to study the effects of ultrasonic vibration on microstructures and microhardness of the parts fabricated by UV-A LENS and LENS without ultrasonic vibration. The results showed that ultrasonic vibration could reduce the porosity, refine the microstructure with a smaller average grain size, and fragment the detrimental phase with a uniform distribution, thus enhancing the microhardness of the fabricated parts.

Peer-review under responsibility of the organizing committee of the 45th SME North American Manufacturing Research Conference

Keywords: Laser engineered net shaping (LENS); Ultrasonic vibration; Inconel 718 alloy; Microstructures; Microhardness

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Peer-review under responsibility of the organizing committee of the 45th SME North American Manufacturing Research Conference
doi:10.1016/j.promfg.2017.07.074

1. Introduction

Laser additive manufacturing (LAM) has become a competitive method for direct fabrication of metal parts with complex structures, due to its advantages of high power density, excellent stability, and easy controllability [1, 2]. LAM technique is mainly divided into powder bed fusion mode and laser beam deposition mode. Compared with the powder bed fusion additive manufacturing such as selective laser melting (SLM), laser engineered net shaping (LENS), a direct laser beam deposition method, has the advantages of part repairing capability, high powder utilizing efficiency, high part building efficiency, etc. [3]. Thus, LENS has been applied as a key technology in fabricating and repairing functional and high added-value metal parts.

In all the applications of LENS process, a high-energy laser beam is used to create a molten pool on a substrate. In the meantime, the powders are continuously delivered into the molten pool by a flowing inert gas stream through the coaxial nozzles, leading to the increase of molten pool volume. Then the molten pool begins to solidify after the leaving of laser beam radiation. As the deposition head moves along the tracking paths, the first layer is deposited on the substrate. Afterwards, the head ascends one-layer thickness to a new position for the next layer deposition. Similar process will be repeated many times until a designed three-dimensional (3D) structure is built layer by layer.

One of the most relevant and important LENS applications focuses on the aircraft turbine components that are usually manufactured or repaired by nickel-based superalloys [4]. Since these superalloys are expensive and exhibit poor machinability, the utilization of LENS enables the reduction of wasted materials, resulting in the decrease of manufacturing costs and increase of productivity. Inconel 718, a type of precipitation hardening nickel-based superalloy, is the most attractive candidate to manufacture or repair the turbines due to its superior properties such as outstanding corrosion resistance, high fatigue strength, and excellent oxidation resistance at elevated temperatures [5]. Recently, LENS of Inconel 718 has attracted great interests in both industry and academia [6]. Many investigations have been conducted to evaluate the microstructures and mechanical properties of LENS-fabricated Inconel 718 parts [7-11]. However, fabrication defects such as pores, cavities, and heterogeneous microstructures are always induced, which are greatly detrimental to the part qualities and mechanical properties of the LENS-fabricated Inconel 718 parts. Therefore, LENS of Inconel 718 parts in a low-cost, high-efficiency, and high-quality way has become a crucial task.

Ultrasonic vibration has been effectively used in melting metal solidification processes such as casting, arc welding, etc. [12-20]. The direct input of ultrasonic vibration results in many nonlinear effects including acoustic streaming and cavitation. With these effects, ultrasonic vibration can help to reduce porosity, refine the microstructure, and increase the homogeneity of chemical contents. Although heat treatment has been utilized as a standardized post-processing method to additionally reduce the porosity and homogenize the microstructures of additively manufactured components, the influence of ultrasonic vibration on the LENS-fabricated parts prior to heat treatment process is desired to be studied. A previous investigation of the authors was carried out in ultrasonic vibration-assisted (UV-A) LENS manufacturing of 17-4 PH stainless steel parts [21]. The results evidenced the fabricated defects reduction induced by the ultrasonic vibration, leading to the improved tensile properties and microhardness. Similarly, finer microstructure and larger microhardness were also achieved in UV-A laser metal deposition of stainless steel 316L by Chen et al. [22]. In addition, Wu et al. [23] utilized ultrasonic vibration to refine microstructures of the zirconia coatings fabricated by laser cladding and modify the dilution characteristics to enhance the coating bonding strength. However, to the best of the authors’ knowledge, there are no reported investigations on UV-A LENS of Inconel 718 parts.

In this paper, UV-A LENS process is utilized to fabricate Inconel 718 parts for the first time, with the purpose to reduce or even eliminate the defects of parts. The experimental investigation is conducted to study the effects of ultrasonic vibration on the part performance in both UV-A LENS and LENS without ultrasonic vibration. Microstructures including porosity, grain size, and featured phases are observed and microhardness of the as-deposited Inconel 718 parts is evaluated.

2. Experimental procedures

2.1. Powder material

Low carbon steel plates with dimensions of 100 mm × 50 mm × 6.4 mm were used as the substrate material. The plate surface was polished and then cleaned by acetone before the LENS fabrication was conducted. The spherical gas atomized Inconel 718 powders (Carpenter Powder Products Inc., Bridgeville, PA, USA) with a particle size range between 45 µm and 125 µm, as shown in Fig. 1, were utilized for part fabrication. The major chemical compositions of Inconel 718 powders were listed in Table 1.

Table 1. The major chemical compositions of Inconel 718 powders.

Element	C	Si	Mo	Nb	Al	Ti	Co	Cr
Wt.%	0.031	0.05	3.05	5.04	0.47	0.9	0.09	19.28

2.2. Experimental set-up and parameters

The LENS process was performed on a customized additive manufacturing machine (450XL, Optomec Inc., Albuquerque, NM, USA) combining with an ultrasonic vibration assisting system. Fig. 2 is a schematic of UV-A LENS system set-up that mainly consisted of a 400W IPG fiber laser system, a chamber system, a powder and inert gas delivery system, a motion control system, and an ultrasonic transducer assembly.

A bulk part with square dimensions of 8 mm × 8 mm × 4 layers was built by both UV-A LENS and LENS without ultrasonic vibration. Each layer was deposited perpendicularly to the previous one to generate a relatively more uniform fabrication than single direction scanning pattern. The cross direction scanning pattern used in this study varied the directions of heat dissipation and temperature gradient. Thus, the continuity of the unidirectional dendrite growth in the previous deposited layer would be broken in the present layer, which could help to form more uniform microstructures. As reported [24], the cross direction scanning pattern would be beneficial to achieve better ductility due to the uniformity of the microstructures. A preliminary parameterization was conducted to obtain the parts with good process conditions where starved or doughy builds should be avoided. In UV-A LENS, the vibration was applied on the substrate and performed in Z direction. The specific LENS manufacturing parameters for Inconel 718 bulk part fabrications were listed in Table 2.

Table 2. The major chemical compositions of Inconel 718 powders.

Parameter	Value	Unit
Laser power	270	W
Powder flow rate	2.63	g/min
Increment of Z axis	0.43	mm
Argon gas flow rate	6	L/min
Scanning speed (contour)	635	mm/min
Scanning speed (infill area)	508	mm/min
Hatch space	0.3	mm
Hatch angle (first layer)	45	°
Hatch angle interval	90	°
Ultrasonic frequency	0, 41	kHz
Ultrasonic power	0, 60	W

2.3. Characterizations of microstructure and properties

After LENS process, samples were prepared by standard metallographic techniques to observe and analyze the microstructure. The sectioned samples were firstly ground and polished on a grinder-polisher machine (MetaServ 250, Buehler, Lake Bluff, IL, USA). Then the samples experienced an ultrasonic clean in acetone to remove contaminations on the surface. In order to reveal the microstructure, the samples were etched in Kalling’s 2 reagent (ES Laboratory, Glendora, CA, USA) for 5 mins. A field emission scanning electron microscopy (FE-SEM) (S4300,

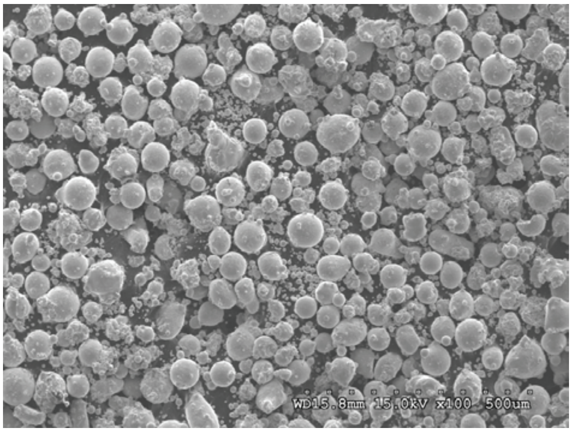

Fig. 1. Inconel 718 powder morphology.

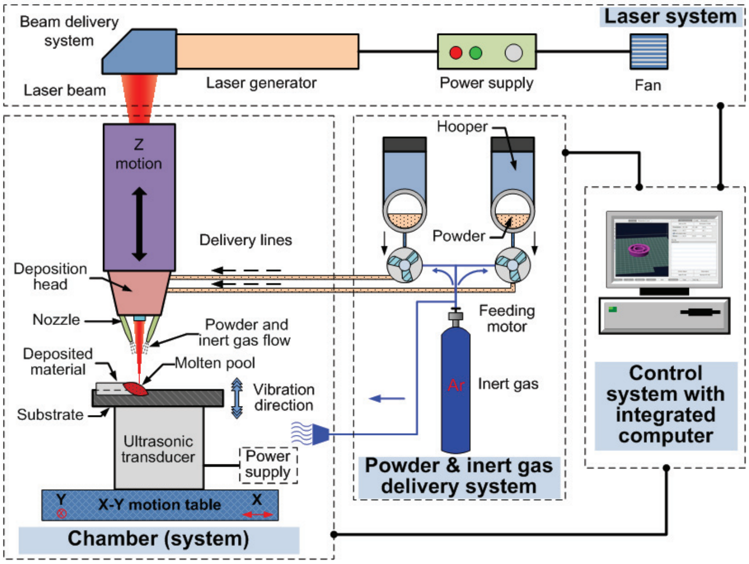

Fig. 2. Schematic of ultrasonic vibration-assisted LENS system set-up.

Hitachi Co., Tokyo, Japan) was used to observe the cross-sectional morphologies and microstructures of the fabricated parts.

Microhardness on the top surface of the polished parts was measured using a Vickers microhardness tester (900–390A Phase II, Metal-Testers Inc., Nanuet, NY, USA). The test was performed at a normal load of 1.96 N and a dwelling time of 15 s. Ten random positions on the parts under each processing condition were selected for the microhardness measurement.

3. Results and discussion

3.1. Porosity

Comparisons on porosity of the parts fabricated by LENS without and with ultrasonic vibration are shown in Fig.

3. It can be clearly observed from Fig. 3a that many large pores were induced in the parts fabricated by LENS without ultrasonic vibration, which was considered as one of the commonly occurred problems in the LENS-fabricated parts. Such phenomenon was caused due to the evolution of entrapped gas bubbles in the molten tracks. These pores were hardly expelled via the top surface prior to the metal solidification in LENS without ultrasonic vibration. The formation of pores would greatly affect the mechanical behavior of the fabricated parts. In the parts fabricated by UV-A LENS process, however, the amount of pores was significantly reduced and the size of pores was much smaller than that in the condition of LENS without ultrasonic vibration, as shown in Fig. 3b. The acoustic streaming and cavitation effects of ultrasonic vibration contributed to such reduction of pores [25]. These nonlinear effects generated the radiation pressure to change the interface between the metallic liquid and inner gas, leading to the collapse of the gas-evolved pores. Therefore, the porosity was significantly decreased in the UV-A LENS fabricated parts. Such phenomena were also found in other UV-A melting metal solidification processes [16].

3.2. Microstructures

In order to reveal the microstructures of crystal grains, the Inconel 718 nickel-based alloy parts fabricated by both UV-A LENS and LENS without ultrasonic vibration were observed using a FE-SEM with a back-scattered electron detector. It can be seen from Fig. 4a that, the parts fabricated by LENS without ultrasonic vibration exhibited the unidirectional and long grain boundaries in the thermal gradient direction. In addition, the grains were in the columnar shapes and their average size in the vertical direction was about 12~15 μm. However, after introducing ultrasonic vibration into the LENS process, the equiaxed grain boundary networks were observed in the parts, which showed more compact and uniform crystal grains with a smaller average grain size of 3~5 μm, as shown in Fig. 4b. Acoustic streaming and cavitation were induced by ultrasonic vibration during the microstructure formation in UV-A LENS. With these actions, a large amount of grain nucleation was produced resulting in the crystal grain refinement in the fabricated parts. It was reported that grain refinement could lead to a high strength and a high hardness, and the well-arranged and homogeneous microstructure could alleviate the residual stress caused during the rapid solidification process in LENS [26, 27].

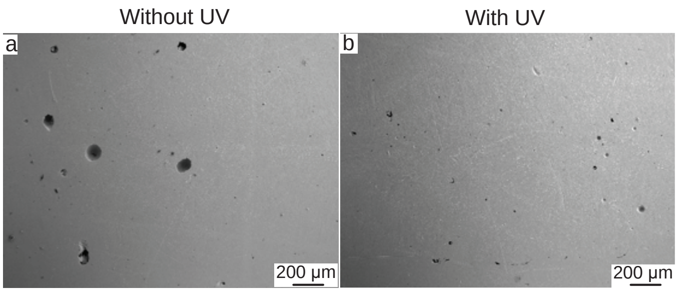

Fig. 3. Comparisons on porosity of the parts fabricated by LENS without and with ultrasonic vibration.

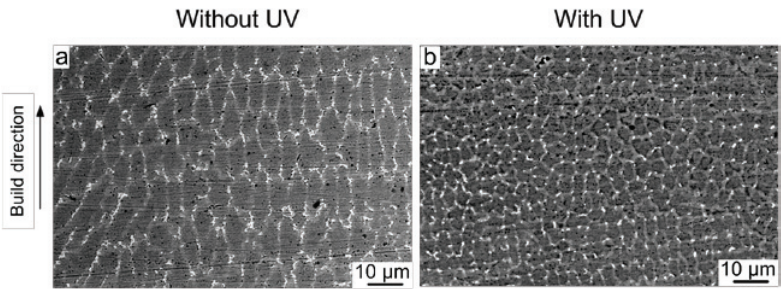

Fig. 4. Grain size evolution under LENS without and with ultrasonic vibration.

Fig. 5 shows the eutectic Laves phase observed by SEM with a secondary electron detector. Laves phase was an intermetallic compound with high concentration refractory elements such as Nb and Mo. It was formed in Inconel 718 alloy as a result of segregation and such phase was considered to be detrimental to the mechanical properties [28]. For example, Laves phase facilitated the crack growth that was harmful for the strength and plasticity of Inconel 718 alloy. In addition, the material precipitation strengthening effects would be weakened as a result of the reduced precipitate number induced by Laves phase [28]. Laves phase was mainly existed as a form of long-bar phase (brighter shapes in Fig. 5a) in parts fabricated by LENS without ultrasonic vibration. However, in UV-A LENS process, ultrasonic vibration generated the radiation pressure in the acoustic field, making the solid-liquid interface unstable. The long-bar shaped Laves phase was therefore fragmented into the small globular phase (brighter particles in Fig. 5b). Due to the actions of liquid agitation induced by ultrasonic vibration, small globular phase uniformly distributed in the matrix phase (darker areas in Fig. 5b). In order to identify the Laves phase, EDS point analysis has been conducted in a larger magnification SEM image of Fig. 5b. It can be seen from Fig. 6 that the matrix (point 1) was rich in Ni, Cr, and Fe, while the white segregation particles (point 2) were rich in Ni, Cr, Nb, and Mo, which were the major compositional elements of the Laves phase. The reduction of the Laves phase segregation caused by ultrasonic vibration would be thus beneficial for the mechanical property enhancement [28].

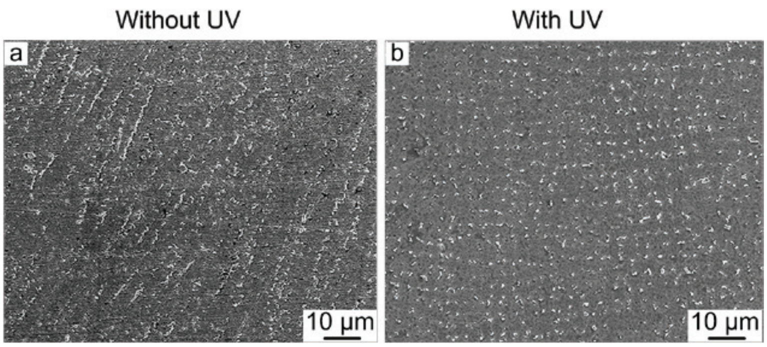

Fig. 5. Comparisons of eutectic Laves phase in the Inconel 718 parts fabricated by LENS without and with ultrasonic vibration.

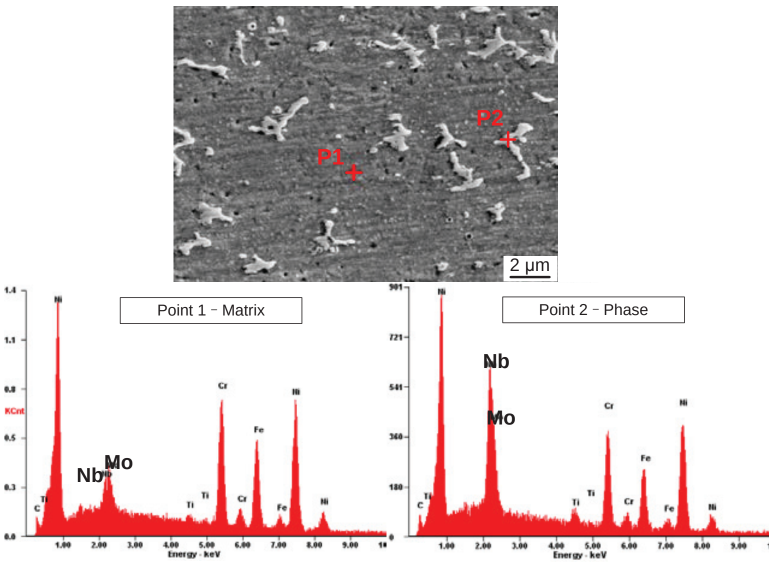

Fig. 6. EDS point analysis results of Inconel 718 parts fabricated by UV-A LENS in Fig. 5b.

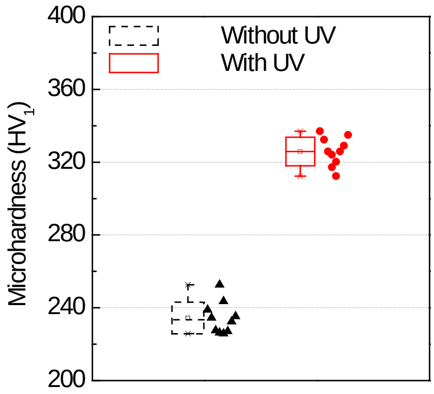

Fig. 7. Microhardness on the top surface of Inconel 718 parts fabricated by both UV-A LENS and LENS without ultrasonic vibration.

3.3. Microhardness

Effects of ultrasonic vibration on microhardness were investigated for both types of parts, as illustrated in Fig. 7. It is notable that ultrasonic vibration resulted in a significant increase of microhardness from the mean value of 233 HV_1 to 328 HV_1 with an increment by 41%. The improvement of microhardness could be explained by the classic Hall-Petch equation in which the microhardness value positively correlated to the reciprocal root of the grain size. That means the decrease of grain size caused by ultrasonic vibration in Section 3.2 resulted in the increase of microhardness. In addition, the decrease of porosity resulted from the ultrasonic vibration evidenced a better fabrication of more uniformly dense parts, improving the part quality with the enhanced mechanical performance.

4. Conclusions

In this paper, ultrasonic vibration was proposed to be utilized in the LENS process for Inconel 718 part fabrication for the first time. Effects of ultrasonic vibration on the microstructures (including porosity, grain size, and Laves phases) and microhardness of the as-deposited Inconel 718 parts were studied in LENS with and without ultrasonic vibration. The results showed that ultrasonic vibration could reduce the porosity, refine the microstructure with a smaller average grain size, and fragment the detrimental Laves phase with a uniform distribution. All these microstructural improvements would further enhance the microhardness of the parts fabricated in UV-A LENS process. In the future work, a comprehensive investigation on the material properties including tensile properties, bonding strength, and wear, fatigue, and corrosion resistances will be conducted to further evaluate the effects of ultrasonic vibration on the part performance.

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