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LASER ENGINEERED NET SHAPING OF METAL POWDERS: A STUDY ON ENERGY CONSUMPTION

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Abstract

With the increasing awareness of environmental protection and sustainable manufacturing, the energy consumptions and potential environmental impacts of laser additive manufacturing (LAM) technology has been attracting more and more concerns. This paper firstly investigates the energy distributions of different modules of laser engineered net shaping (LENS), studies the effects of input variables (laser power, scanning speed, and powder feed rate) and kinds of powders on the overall energy consumption during laser deposition processes. The Energy Consumption of Unit Deposition Volume (ECUDV, in J/mm^3) is proposed as a measure for the average applied energy per volume of deposited material. The experimental results suggest that the powder feed rate has the largest effect on ECUDV, followed by scanning speed and laser power. When the geometry shaping is selected as an evaluating criterion, AISI 4140 powder will cause the largest energy consumption per unit volume.

Keywords
Laser engineered net shaping; Energy consumption; laser power; Scanning speed; Powder feed rate

Introduction

Laser engineered net shaping (LENS) is now serving as one of the key technologies in the direct manufacturing or repairing of metal parts. Starting from a Computer Aided Design (CAD) solid file, the LENS process produces parts layer by layer from bottom up with the heat input of a high-powered laser. Compared to traditional surface treatment processes, LENS has a higher repair efficiency, less post processing, higher cooling rate, and smaller heat affected zone thus achieving better mechanical behaviors after deposition processes [1]. Holding these advantages, LENS has ability to fabricate near-net-shaped prototypes, high quality metal parts, and even special tooling for injection mold [2]. Recently, LENS has been successfully applied in direct fabrication of complex structural components [3], functionally graded coatings [4], high-value added components repair [5], and special occasions such as aerospace, defense, biomedical, etc. [6].

With the increasing awareness of energy saving and environmental protection, environmental issues have aroused more concerns during product manufacturing processes. Both governments and corporations are being pushed to pay more attention to the environmental burdens of the product. Since developed by Sandia National Laboratories in 1997, LENS has exhibited a great potential to revolutionize the way for metal parts fabrication and attracted more and more concerns in both academia and industries. In the last decades, extensive research has been conducted on the optimization of mechanical properties and microstructures of components fabricated by LENS [7-14], and thermal modeling and control over the entire powder deposition process [15-19]. These investigations have provided a clear understanding on the characteristics of LENS and promoted this technology as a major step towards actual industrial applications.

Energy consumption analysis is the very first step and essential for energy saving technologies development and scientific environmental assessment for LENS. During the powder deposition process, several modules including high-powered laser generation, powder feeding and delivery, and motion control will cause significant electricity energy consumption. The input variables will also affect the total power consumption and distribution to a large extent. Several studies have been conducted to evaluate the power consumption of the

LENS system. The focus was the identification of laser energy transfer efficiency or power distribution routes during deposition process. However, the energy input and distribution were obtained through indirect measurement and modeling method [20-22]. The literature review suggests that the experimental analysis for energy consumption in LENS has not attracted much attention, and the effect of input variables, such as laser power, scanning speed, powder feed rate on energy consumption is rather limited.

This study is the first to investigate the energy consumption in LENS of metal powders. An energy consumption measurement system is set up and a series of experiments are conducted to analyze the energy consumptions quantitatively in LENS process. The energy distribution of different modules of LENS, the effects of input variables (including laser power, scanning speed and powder feed rate) and kinds of powders (including Inconel 718, Stellite 1, Tribaloy T-800 and AISI 4140) on the energy consumption during laser deposition processes are extensively investigated. It also provides the percentage of each module's energy consumptions relative to the entire LENS system's energy consumption under different experimental conditions. This paper includes four sections, following this introduction section, section 2 describes the materials, experimental set up, experimental conditions and measurement procedures. Section 3 presents and discusses of the experimental results, and conclusions are summarized in section 4.

Materials and Methods

Material properties

It has been reported that nickel-based, cobalt-based, and iron-based materials are commonly used powders during LENS processes [23]. Considering the range of materials availability in LENS and the principle of joining dissimilar materials using a laser beam [24], Inconel 718 (nickel-based), Stellite 1 (cobalt-based), Tribaloy T-800 (cobalt-based) and AISI 4140 (iron-based) are selected as the candidate fabricating materials. The AISI 4140 square plates are utilized as the substrate. The material properties are shown in Table 1.

Table 1. Properties of selected materials

Type	Cladding material	Particle size (micron)	Hardness (HRC)	UTS (MPa)	Density (g/cm^3)
Ni-based	Inconel 718	44/125	42-44	1241	8.19
Co-based	Stellite 1	45/150	50-58	1195	8.69
	Tribaloy t-800	53/149	55-60	1778	8.64
Fe-based	AISI 4140	44/105	31-39	1000-1200	7.85

Experimental set-up

The experiment was carried out using an Optomec LENS 450 Workstation, equiped with a high powered IPG 400W fiber laser, a pneumatic powder delivery system, and a computer-controlled motion system. The powder feeder system is controlled by computer and motorized with revolutions-per-minute adjustment to meter the amount of powder flow. The powder material is deposited onto the substrate conveyed by an argon protective gas through the coaxial nozzles on a four-jet deposition head. A high power laser is used to melt metal powder at the focus of the laser beam and the motion table is moved to fabricate the object layer by layer. The illustration of the complete LENS system is shown in Figure 1.

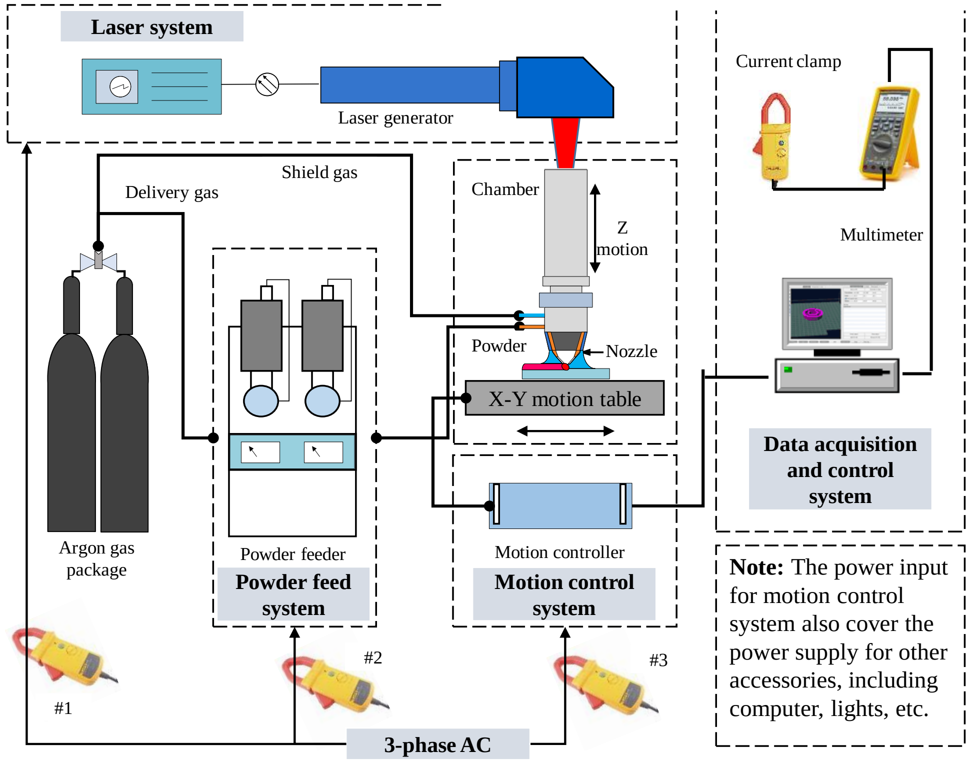

Figure 1. Illustration of experimental set-up

Three modules of the LENS system will require energy input: (1) laser power system, (2) powder feed system, and (3) motion control system. During the powder deposition process, each module requires one power cord (#1~#3). A data acquisition system is set up for the measurement of voltage and current of power supply. The system includes a current clamp (Fluke i410), a multi-meter (Fluke 289), and a computer with Fluke-view Forms software.

The relationship between input variables (laser power, scanning speed, and powder feed rate) and overall energy consumption is investigated through a single factor experiment. Totally, 16 blocks are deposited and the size and shaping of the blocks is shown in Figure 2 and the values of the variables are shown in Table 2.

Table 2. Values of input variables

Variable	Value	Attribute
Laser power (W)	275, 300, 325, 350	Variable
Scanning speed (mm/s)	6.35, 8.47, 10.58, 12.7	Variable
Powder feed rate (rpm)	2.5, 3.0, 3.5, 4.0	Variable
Layer thickness (mm)	0.43	Constant
Gas flow rate (L/min)	6	Constant
Number of layers	4	Constant

Energy consumption measurement

The amount of electricity used in the LENS is measured when depositing a block onto the substrate material (the base area of the block is: 7.62*7.62 mm^2). The energy consumption of unit deposition volume (ECUDV, in J/mm3) is a measure for the averaged applied energy per volume of material during the deposition of a block:

$$E = \frac{PT}{V} = \frac{U[I_l(T_t - T_i) + (I_f + I_s)T_t]}{S \times h} \quad (1)$$

where,

E: volumetric energy input, J/mm^3;
P: Input power, W;
V: Volume of the deposited block, mm^3;
U: System voltage, 240V;
T: Process time, s;
T_t: Total time, s;
T_i: Idling time, s;
I_l: Current of laser system, amps;
I_f: Current of powder feeder system, amps;
I_s: Current of motion control system, amps;
S: Bottom area of the block, 7.62*7.62 mm^2;
h: Height of the block, mm (measured by caliper).

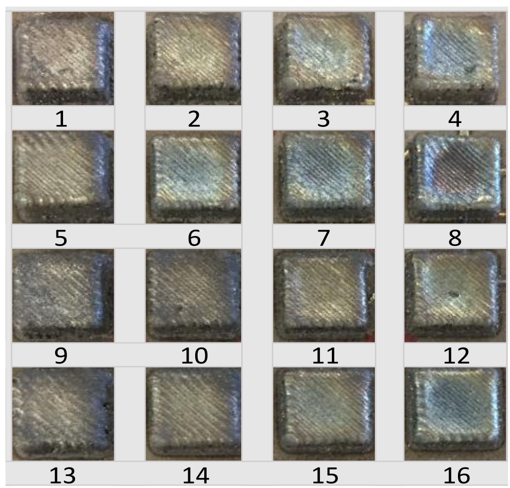

Figure 2. The dimension and shaping of the deposited blocks

Results and discussion

The experimental data is analyzed by Minitab 17 and the response value of average energy consumption is shown in Table 3, which suggests that the powder feed rate has the largest effect on ECUDV, followed by scanning speed and laser power.

Table 3. Response value of average energy consumption

Level	Laser power (W)	Scanning speed (mm/s)	Powder feed rate (rpm)
1	917.1	1093.5	1215.7
2	892.1	893.6	931.1
3	998.2	899.2	915.8
4	1036.6	957.6	781.3
Delta	144.5	199.9	434.4
Rank	3	2	1

Effects of laser power

The effects of laser power on the ECUDV is shown in Figure 3 (powder: IN718). Theorecticaly, the energy consumption should be increasing when the power input increases, however, the energy consumption decreases when the laser power increases from 275W to 300W. This is possibly because the powders are not totally melted under 300W, and the porosity rate is higher which causes a bigger block. When the laser power keeps increasing, the powders are totally melted, and unit energy consumption increased as is theoretically indicated.

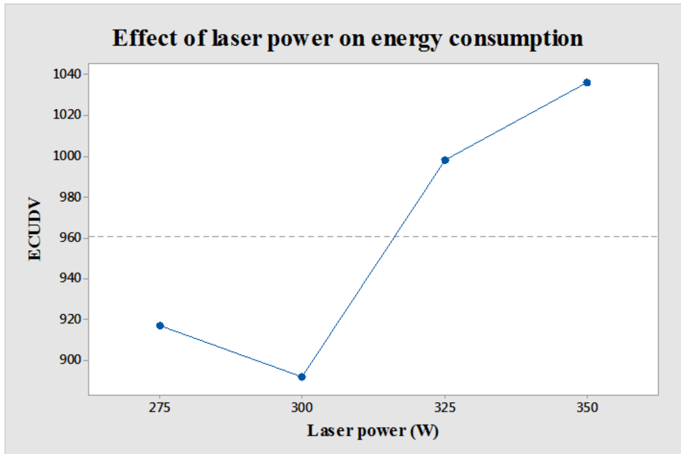

Figure 3. Effect of laser power on energy consumption

The energy distribution of different modules (laser power system, powder feed system and motion control system) under different laser power are shown in Figure 4. The results show that the energy consumption of the laser system increased from 63.37% to 69.42% when laser power input increased from 275W to 350W. The increase of power would not affect the current change of powder feeder and motion control systems, thus, the energy consumption of these two modules remained nearly the same when the laser power input increased.

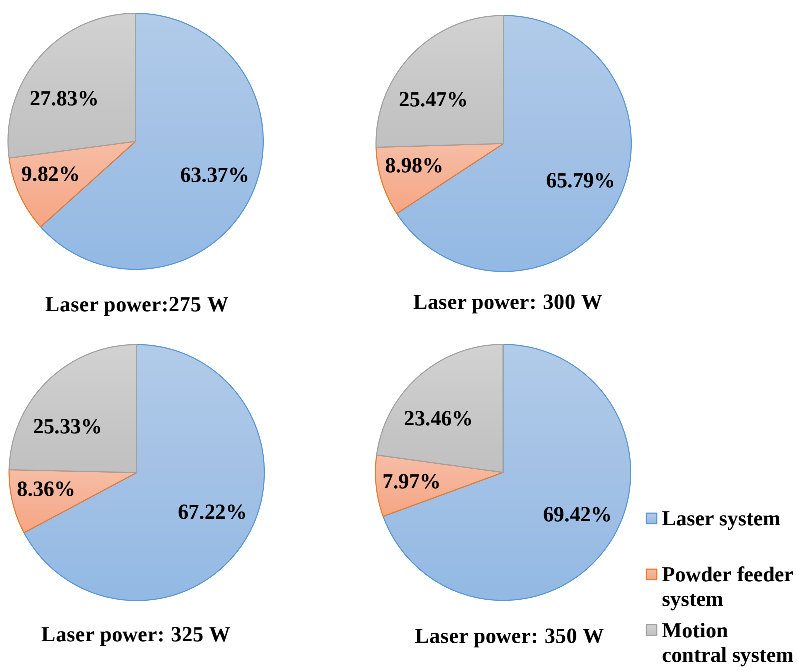

Figure 4. Energy distributions under different laser power: (Powder: Inconel 718, Powder feed rate: 4rpm, Scanning speed: 12.7 mm/s)

Effects of scanning speed

Effect of scanning speed on the overall energy consumption is shown in Figure 5. Theoretically, when the scanning speed increased from 6.35 mm/s to 12.7 mm/s, the unit energy consumption should present a decreasing trend because when the scanning speed increased, the process time reduces, and the total energy input reduced correspondingly from a theoretical standpoint. However, when the scanning speed changes from 8.47 mm/s to 12.7 mm/s, there is not enough time for the powders to be totally melted [25], therefore, the actual volume of the deposited block decreases, and it becomes the dominant factor, which causes the increasing of the unit energy consumption.

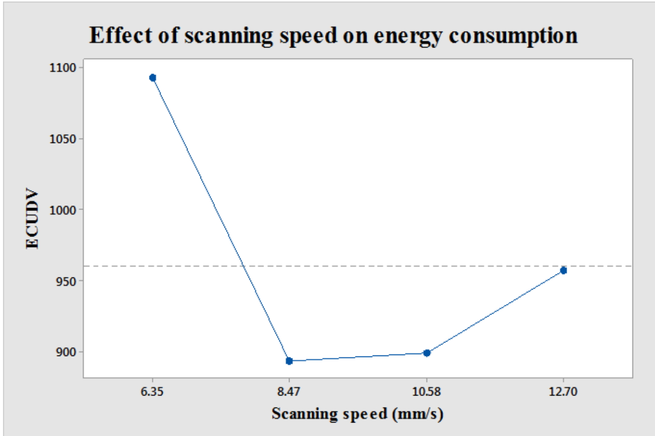

Figure 5. Effect of scanning speed on energy consumption

Energy consumption percentages of each module under different scanning speed is shown in Figure 6. As scanning speed increases from 6.35 mm/s to 12.7 mm/s, the energy consumption percentages of laser system, powder feed system and motion control system did not change much and remained as approximately 68%, 8% and 23% respectively.

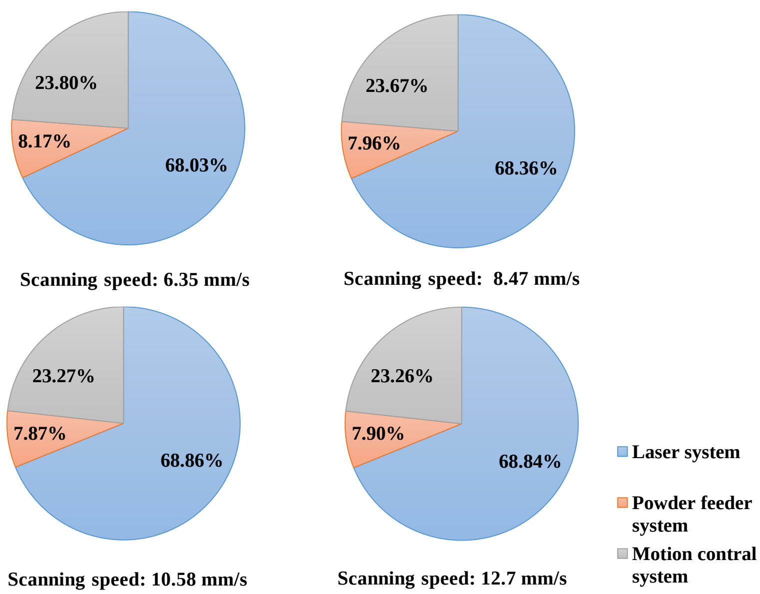

Figure 6. Energy distributions under different scanning speed: (Powder: Inconel 718, Laser power: 350W, Powder feed rate: 2.5 rpm)

Effects of powder feed rate

For the effect of powder feed rate, equation (1) suggests that it will not affect the volume of the final block, however, when the powder feed rate increases from 2.5 rpm to 4 rpm, the height of the deposited block will be significantly increased, which causes the increase of the volume, therefore, the actual unit energy consumption value decreases (as is shown in Figure 7).

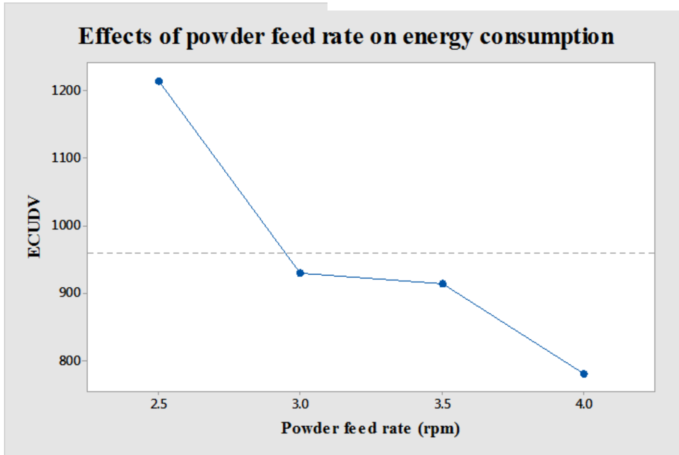

Figure 7. Effect of powder feed rate on energy consumption

Energy consumption percentages of each module under different powder feed rate is shown in Figure 8. As powder feed rate is varied from 2.5 rpm to 4 rpm, the energy consumption percentages of laser system, powder feed system and motion control system did not change much and remained as approximately 68%, 8% and 23% respectively, which is similar to the energy distribution trend generated by scanning speed.

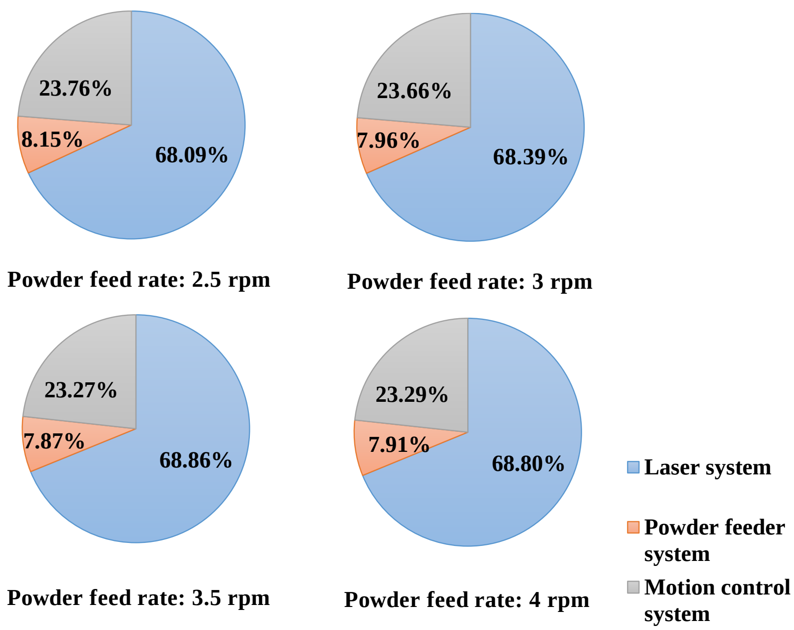

Figure 8. Energy distributions under different powder feed rate: (Powder: Inconel 718, Laser power: 350W, Scanning speed: 10.58 mm/s)

Effects of metal powders

Due to the different property of the powders, the best clad quality will occur at different conditions (parameters combinations). Given the condition that the final clad quality is the best, the effect of powders on the unit energy consumption is examined and the result is shown in Figure 9. AISI 4140 will cause the highest energy consumption, followed by IN 718, Triboloy 800 and Stellite 1. The reason is that for different powders, the power absorption rate is different (AISI 4140 has the lowest laser power absorption rate within selected powders), and interaction of the power and powder is also different which brings about different energy requirements.

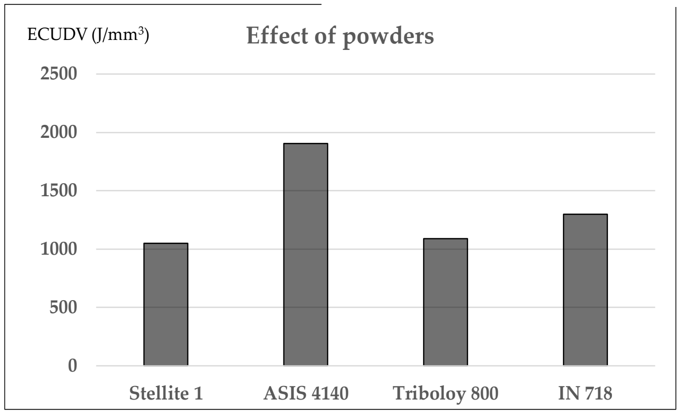

Figure 9. Effect of powder materials on energy consumption

Conclusions

This paper analyzed the energy consumptions of the LENS process, the effect of input variables, powders on energy consumption is investigated in detail. The following conclustions can be drawn from the study.

- The total energy consumption of the laser system increased from 63.37% to 69.42% when laser power input increased from 275W to 350W. When the scanning speed and powder feed rate increases, the energy consumption percentage of each modules approximately remains the same.

- The energy consumption (ECUDV) decreases when the laser power increases from 275W to 300W possibly because the powders are not totally melted and the porosity rate is higher which causes a bigger block. When the laser power keeps increasing, the powders are totally melted, and unit energy consumption increased as is theotectically indicated;

- When the scanning speed changes from 8.47 mm/s to 12.7 mm/s, there is not enough time for the powders to be totally melted, therefore, the actual volume of the deposited block decreases, which causes the increase of the unit energy consumption;

- The height of the deposited block is significantly increased when the powder feed rate increases from 2.5 rpm to 4 rpm, which causes the increase of the volume, therefore, the actual unit energy consumption value decreases;

- AISI 4140 will cause the highest energy consumption (ECUDV), followed by IN 718, Triboloy 800 and Stellite 1.

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References

1. Xu, M., Li, J., Jiang, J., & Li, B. Influence of Powders and Process Parameters on Bonding Shear Strength and Micro Hardness in Laser Cladding Remanufacturing. *Procedia CIRP*, 2015. 29, 804-809.
2. Atwood, C., Griffith, M. L., Schlienger, M. E., Harwell, L. D., Ensz, M. T., Keicher, D. M., ... & Smugeresky, J. E. Laser engineered net shaping (LENS): a tool for direct fabrication of metal parts. *Conf Lasers Electro Optics*, 1998, Vol. 98, pp. 16-19.
3. Jeantette, F. P., Keicher, D. M., Romero, J. A., & Schanwald, L. P. *U.S. Patent*, No. 6,046,426. 2000, Washington, DC: U.S. Patent and Trademark Office.

4. Pei, Y. T., & De Hosson, J. T. M. Functionally graded materials produced by laser cladding. *Acta Mater*, 2000, 48(10), 2617-2624.
5. Dong, S., Yan, S., Xu, B., Wang, Y., & Ren, W. Laser Cladding Remanufacturing Technology of Cast Iron Cylinder Head and Its Quality Evaluation. *J Acad Arm Force Eng*, 2013, 27(1), 90-93.
6. Santos, E. C., Shiomi, M., Osakada, K., & Laoui, T. Rapid manufacturing of metal components by laser forming. *Int J Mach Tool Manu*, 2006, 46(12), 1459-1468.
7. Tabernero, I., Lamikiz, A., Martínez, S., Ukar, E., & Figueras, J. Evaluation of the mechanical properties of Inconel 718 components built by laser cladding. *Int J Mach Tool Manu*, 2011, 51(6), 465-470.
8. Majumdar, J. D., Pinkerton, A., Liu, Z., Manna, I., & Li, L. Mechanical and electrochemical properties of multiple-layer diode laser cladding of 316L stainless steel. *Appl Surf Sci*, 2005, 247(1), 373-377.
9. Qi, H., Azer, M., & Ritter, A. Studies of standard heat treatment effects on microstructure and mechanical properties of laser net shape manufactured Inconel 718. *Metall Mater Trans A*, 2009, 40(10), 2410-2422.
10. Zhao, X., Chen, J., Lin, X., & Huang, W. (2008). Study on microstructure and mechanical properties of laser rapid forming Inconel 718. *J Mater Sci Eng A*, 478(1), 119-124.
11. Zhong, M., Liu, W., Yao, K., Goussain, J. C., Mayer, C., & Becker, A. Microstructural evolution in high power laser cladding of Stellite 6+ WC layers. *Surf Coat Technol*, 2002, 157(2), 128-137.
12. Nurminen, J., Näkki, J., & Vuoristo, P. Microstructure and properties of hard and wear resistant MMC coatings deposited by laser cladding. *Int J Refract Metals Hard Mater*, 2009, 27(2), 472-478.
13. Niu, H. J., & Chang, I. T. H. Microstructural evolution during laser cladding of M2 high-speed steel. *Metall Mater Trans A*, 2000, 31(10), 2615-2625.
14. Dubourg, L., Ursescu, D., Hlawka, F., & Cornet, A. Laser cladding of MMC coatings on aluminium substrate: influence of composition and microstructure on mechanical properties. *Wear*, 2005, 258(11), 1745-1754.
15. Zheng, B., Zhou, Y., Smugeresky, J. E., Schoenung, J. M., & Lavernia, E. J. Thermal behavior and microstructural evolution during laser deposition with laser-engineered net shaping: Part I. Numerical calculations. *Metall Mater Trans A*, 2008, 39(9), 2228-2236.
16. Zheng, B., Zhou, Y., Smugeresky, J. E., Schoenung, J. M., & Lavernia, E. J. Thermal behavior and microstructure evolution during laser deposition with laser-engineered net shaping: part II. Experimental investigation and discussion. *Metall Mater Trans A*, 2008, 39(9), 2237-2245.
17. Griffith, M. L., Ensz, M. T., Puskar, J. D., Robino, C. V., Brooks, J. A., Philliber, J. A., ... & Hofmeister, W. H. Understanding the microstructure and properties of components fabricated by laser engineered net shaping (LENS). *Mater Res Soc Symp Proc*, 2000, 625, 9.
18. Ye, R., Smugeresky, J. E., Zheng, B., Zhou, Y., & Lavernia, E. J. Numerical modeling of the thermal behavior during the LENS® process. *J Mater Sci Eng A*, 2006, 428(1), 47-53.
19. Wang, L., & Felicelli, S. Analysis of thermal phenomena in LENS™ deposition. *J Mater Sci Eng A*, 2006, 435, 625-631.
20. Unocic, R. R., & DuPont, J. N. Process efficiency measurements in the laser engineered net shaping process. *Metall Mater Trans B*, 2004, 35(1), 143-152.
21. Pinkerton, A. J., & Li, L. An analytical model of energy distribution in laser direct metal deposition. *Proc Inst Mech Eng B J Eng Manuf*, 2004, 218(4), 363-374.
22. Gedda, H., Powell, J., Wahlström, G., Li, W. B., Engström, H., & Magnusson, C. Energy redistribution during CO2 laser cladding. *J Laser Appl*, 2002, 14(2), 78-82.
23. DONG, S., MA, Y., XU, B., & HAN, W. Current Status of Material for Laser Cladding. *Mater Rev*, 2006, 6(2), 5-13.
24. Sun, Z., & Ion, J. C. Laser welding of dissimilar metal combinations. *J Mater Sci*, 1995, 30(17), 4205-4214.
25. Fathi, A., Toyserkani, E., Khajepour, A., & Durali, M. Prediction of melt pool depth and dilution in laser powder deposition. *J Phys D Appl Phys*, 2006, 39(12), 2613-2323.