Characterization on Laser Direct Manufacturing Metal Thin Wall Cylinder

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Abstract Laser direct manufacturing is a novel manufacturing technology. Fe-Cr-B-Si-C alloy powders are used in laser direct manufacture to make single track laser cladding layer and thin wall cylinder. The microstructure, phase structure and mechanical properties of single track cladding layer and thin wall cylinder are investigated by optical microscopy (OM), energy dispersive X-ray analysis (EDX), X-ray diffraction (XRD) and nano-indentation techniques. The results show that laser direct forming metal parts are fully dense, and that there are no defects such as crack and pore. There is somewhat coarsening during interlayer microstructure, which can lead to weak mechanical properties. However, the whole properties of the thin wall cylinder may still satisfy the real part performance requirements. The change of laser scanning direction is beneficial to molten pool stirring, which leads to smashed dendrite structure in favor of microstructure homogenization.

Key words laser technology; laser direct manufacture; microstructure; mechanical properties

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激光直接制造薄壁圆筒零件的特性

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摘要 激光直接制造是一种全新的制造技术。采用Fe-Cr-B-Si-C铁基合金粉末利用激光直接制造技术制备了单道激光熔覆层和薄壁圆筒零件。运用金相显微镜(OM)、X射线能谱仪(EDX)、X射线衍射(XRD)和纳米压痕技术研究了单道激光熔覆层和薄壁圆筒零件的显微组织、物相结构和纳米力学性能。研究结果表明,激光直接制造金属零件组织致密、未出现裂纹和气孔等缺陷;层间组织发生了粗化,导致层间力学性能弱化,但整体性能较高,能够满足实际零件的使用性能要求;激光扫描方向的改变有利于熔池的搅拌作用,枝晶组织发生了碎化,有利于组织的均匀化。

关键词 激光技术;激光直接制造;组织;力学性能

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1 Introduction

Currently metal parts are produced by thermo-mechanical process, which include casting, rolling forging, extrusion, machining and welding operations. Multiple steps are required to produce the final parts. These conventional operations often require the use of heavy equipment and molds. Conventional operations show obvious advantages on fabrication of parts in large volume. However, when the part is unusual in shape or it has fine internal features, the turn-around and cost will increase rapidly, and in some cases it is impossible to realize.

Laser direct manufacturing (LDM) is a novel additive manufacturing technology that uses a laser

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beam to melt and deposit the injected powder and shapes component directly from CAD model. It is an extension of laser cladding process for 3D component fabrication by multi-layer overlapped deposition. Due to its rapid solidification characteristic, the produced metal part is of superior quality and performance. Distinct from the conventional machining process, it has the capability to fabricate near-net shape 3D components with short turn-around time and eliminate many steps of manufacturing (e.g. drawing preparation, specific size raw material procurement, man- machine- process planning and intermittent quality checks) and allied human errors[1-7].

Laser direct manufacturing technology is an advanced manufacturing technology, which has already obtained some successful applications [8-11].In this paper, laser rapid manufacturing technology was employed to fabricate metal thin wall cylinder with the dimension of 30 mm in diameter, 50 mm in height and 30 mm in thickness. The microstructure and mechanical property of the sample were also investigated. We hope our study can provide theoretical guidance on the application of laser rapid manufacturing to equipment parts.

2 Experiment

18Cr2Ni4WA steel was used as substrate material. Before the laser cladding treatment, the surface of 18Cr2Ni4WA was polished with silicon carbide abrasive papers and cleaned with acetone. Fe-Cr-B-Si-C alloy powder with an average particle size ranging from -140 mesh to +320 mesh was selected as laser cladding material. Its nominal chemical composition is shown in table 1. In order to eliminate the moisture, the powders were oven dried over 2 h in vacuum drying furnace with 120℃ before experiment.

Table 1 Nominal chemical composition of Fe-Cr-B-Si-C alloy

Element	Cr	B	Si	C	Fe
Weight percentage /%	13.5	1.65	1.15	0.15	Bal.

The experiments were carried out using a 1 kW continuous wave Nd:YAG laser with 1.064 μm wavelength and 2 mm diameter optical fiber. The apparatus used is illustratedin Fig.1, and it can be described in terms of four interacting systems, which were termed as laser system, material delivery system, robot control system, gas protection system. The metal powders were delivered by argon gas from a powder feeder, passing through a lateral powder nozzle into molten pool. The optimized processing parameters were selected as: 1 kW power, 5 mm/s scanning speed and Φ2 mm laser beam diameter, 6 g/min powder feeding velocity, 0.25 mm single layer deposition thickness. Argon gas was used to protect the surface oxidation during laser manufacturing process.

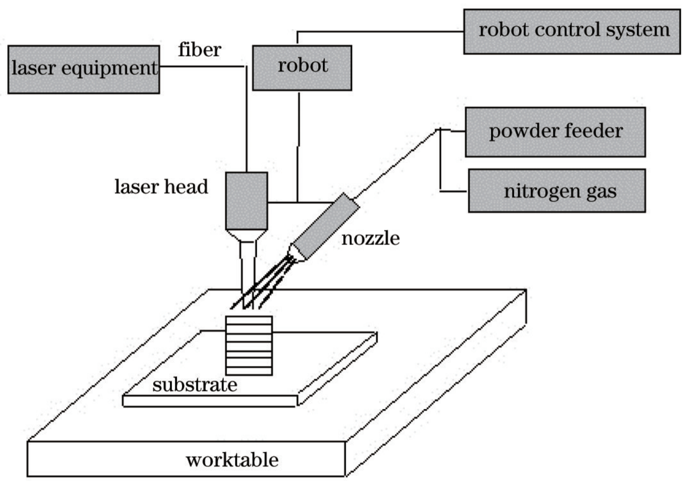

Fig.1 Schematic diagram of experimental apparatus

The microstructure characterization of the sample was analyzed by optical microscopy (OM). The composition of the sample was measured by energy despersive X-ray analysis (EDX). Phase structures were determined by means of X-ray diffraction (XRD) with Cu Kα (λ=15.4 nm) radiation on a D8-advance apparatus. The micro-hardness was measured by a micro-hardness tester (HVS-1000). The hardness and the elastic modulus of the sample were investigated using the nano-indentation tester (Nano-test 600) with the largest load of 15 N·m and the load and uninstall velocity of 0.3 mN/s under the 100 μm measured point interval.

3 Results and discussion

3.1 Microstructure of single path laser cladding layer

The laser forming metal part is built point by point, line by line, and layer by layer. Good quality of the single laser cladding layer is very important for manufacturing three-dimension metal part. Good layers require good shapes and appearance, continuous and smooth surface, low dilution, dense microstructure, no pores and crack defects. Figure2 shows the cross-sectional microstructure of a single laser clad layer. It can be found that the coating is free from pores and cracks defect, and has strong bonding with the substrate and very low dilution. Three different zones (planar growth zone, dendritic and equiaxial zone) can be distinguished clearly from molten bottom to surface. As is known, the solidification microstructure is mainly determined by the solidification conditions, namely temperature gradient G and solidification rate R. Generally speaking, G/R ratio largely influences the growth morphology. From fusion line to clad surface, the solidification rate R increases, and at the same time the temperature gradient G decreases gradually. As a result, the ratio of G/R decreases gradually. The constitutional super-cooling rate becomes large. The solidification structure converts successively to planar, dendritic and equiaxial microstructure.

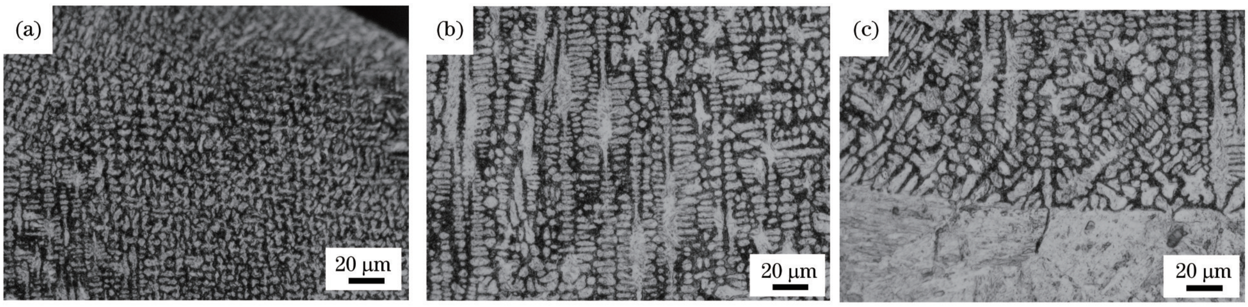

Fig.2 Cross sectional microstructure of single path laser cladding coating. (a) Top region; (b) middle region;(c) bottom region

3.2 Laser direct manufacturing thin wall cylinder

The laser forming thin wall cylinder was carried out through multiple layer cladding. Result of XRD analysis, as shown in Fig.3, indicates that the main constitution phases of the laser forming thin wall cylinder are γ-Fe、CrFeB and $Cr_{12}Fe_{36}Mo_{10}$.

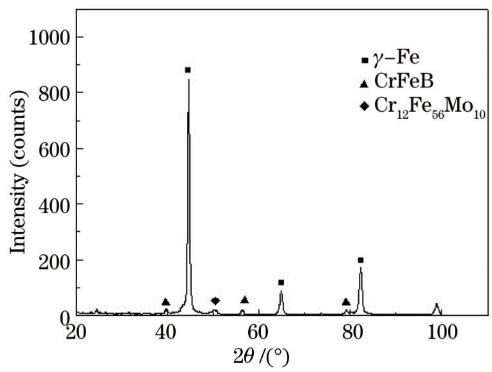

Fig.3 X-ray diffraction spectra of laser forming thin wall cylinder

Figure4 is an optical micrograph of the laser direct manufacturing thin metallic cylinder from transverse cross section.

It can be found that the coating is free from pores, micro-cracks and other defects. From Fig.4(a), we can find that the microstructure of thin wall cylinder shows layer structure.There are different microstructures between interlayer and layer. Because laser direct manufacturing metal part is stacking process in layer by layer pattern, any solidified point is subjected to reheat and cooling circulation process. The effect of annealing and tempering during successive layer deposition can lead to the growth of grain size and form coarsening microstructure [see in Fig.4(b)], which forms marked layer structure. Laser direct forming has characteristics of high temperature gradient,solidification velocity and super-rapid cooling rate. These can lead to fine microstructure due to high nucleation rate and short growth time. A strong stirring action in the laser molten pool is an effective method to improve microstructure and element uniformly. During the fabrication process of the thin wall cylinder, the substrate sample was fixed on a work table and the laser beam was in circle track movement. Thus laser scanning direction can be altered at any time during laser forming process. The change of laser scanning direction is beneficial to molten pool stirring, which lead to smashed dendrite structure in favor of microstructure homogenization. This reduces dendrite amount and increases fine grains amount in the laser cladding layer, see in Fig.4(c). So, the directional dendrite do not disappear in the thin wall sample. Fig.4(d) is an optical micrograph of interface between substrate and laser forming cylinder. It is obvious that there is a metallurgical interface bonding between the coating and the substrate. Dilution had little effect on the substrate. This diluted portion was parted away while separating from the substrate. Thus, the final fabricated part did not have any dilution. Elemental analysis of energy by EDX was carried out. Figure5 shows the EDX line scan analysis for trend in concentration changes of the laser direct wall cylinder sample. It can be seen that there is a weak change of Fe and Cr. So there is no composition segregation during laser forming process.The improvement of elemental segregation of sample relates to two factors: firstly, under the condition of the excessively high temperature gradient and rapid solidification rate, the solidification process departs from the equilibrium state obviously. Accordingly, the solute catch effect enhances so that the solute partition coefficient drives to 1, so the composition of solidification tends to the average composition of alloy powder. Secondly, the exceeding refining of microstructure leads to the uniform effect of alloy elements.

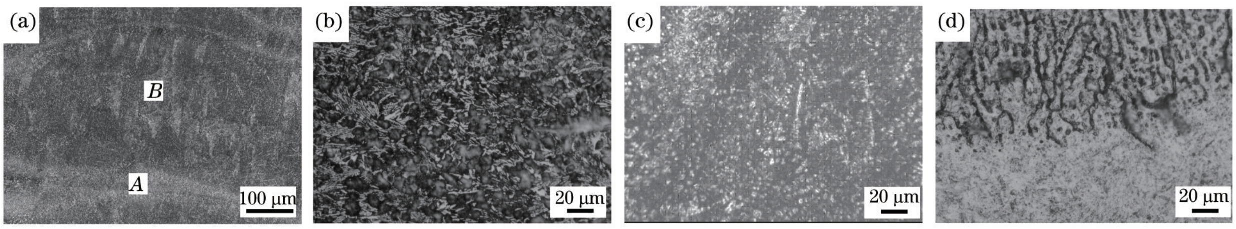

Fig.4 Microstructure of laser direct manufacturing metallic cylinder part. (a) Whole sample; (b) high magnification morphology of *A* region; (c) high magnification morphology of *B* region; (d) interface between substrate and cladding

Figure6 shows the actual laser direct manufacturing thin cylinder component. Dye penetrant testing (DPT) and ultrasonic test (UT) of cylinder were carried out to detect defects. No cracking and porosity appeared in the manufactured component. This result is in agreement with above microstructure observation. During laser forming process, since alloy powder cannot completely feed into molten pool, a part of powder adhered to the heated cylinder surface. A number of partially melted adherent particles on the cylinder surface were observed which affected the dimension precision and surface roughness. The feeding system can be improved, such as coaxially feeding or using laser re-melting process to improve the surface quality.

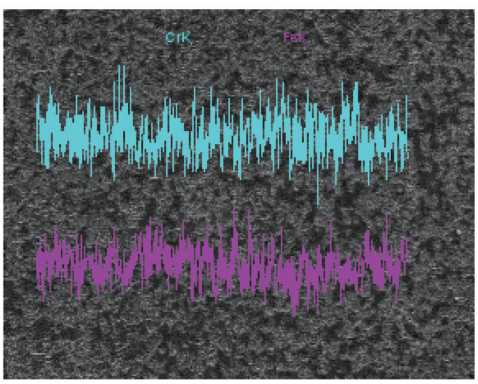

Fig.5 EDX line scan analysis for trend in concentration change of cylinder sample

Fig.6 Laser direct manufacturing thin cylinder component

3.3 Mechanical performances

A micro- structural homogeneity plays an important role in producing uniform mechanical performances. In the laser rapid forming parts, coarsening of track and layer in the overlapping zone is a commonly encountered problem. The grain coarsening is caused by heating effect by the conducted heat of the solidified pool of the next layer, and in the subsequent layer the interface was coarsened in the same fashion. It is possible to age or temper the material, which can affect the material's mechanical properties. Figure7 and Fig.8 show the distribution curves of hardness and elastic modulus along height direction of laser direct forming cylinder sample. From Fig.7 and Fig.8, it can be found that there are some fluctuations in mechanical performance such as hardness and elastic modulus. This is due to layer and layer stacking during laser direct manufacturing process. There is somewhat coarsening during interlayer microstructure, which can lead to weak mechanical properties such as hardness and elastic modulus. However, the whole properties of the thin wall cylinder may still satisfy the practical part performance requirements.

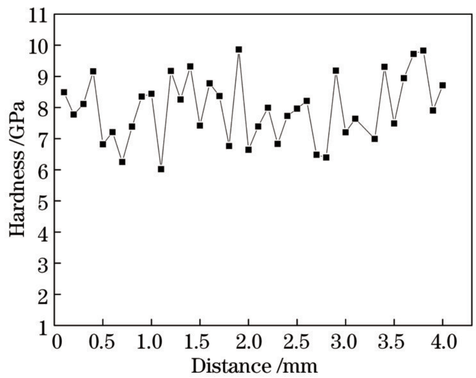

Fig.7 Micro-hardness distribution along height direction of laser direct forming cylinder part

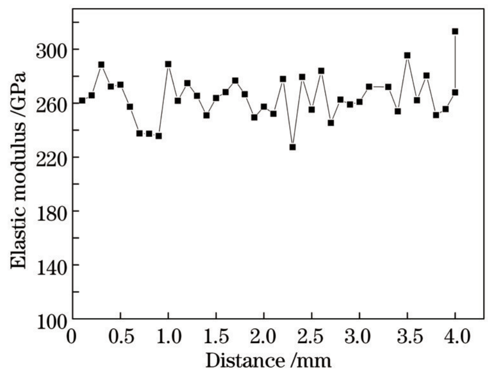

Fig.8 Elastic modulus distribution along height direction of laser direct forming cylinder part

4 Conclusions

1) Laser direct manufacturing thin wall cylinder sample is fully dense with fine microstructure and uniform composition. The change of laser scanning direction is beneficial to molten pool stirring, which leads to smash dendrite structure in favor of microstructure homogenization.

2) There are some fluctuations in mechanical performance such as hardness and elastic modulus. This is due to layer and layer stacking, which can lead to coarsening during interlayer microstructure. However, the whole properties of the thin wall cylinder may still satisfy the practical part performance requirements.

3) The adherent particles on the cylinder surface affect the dimension precision and surface roughness. Feeding system can be improved, such as coaxially feeding or using laser re-melting process to improve the surface quality.

References

1 Liu Xiubo, Yu Yongmin. Recent developments in laser surface treatments and rapid manufacturing [J]. Laser & Optoelectronics Progress, 2005, 42(4): 48-52.
刘秀波, 于永民. 激光表面处理和快速制造技术的新进展[J]. 激光与光电子学进展, 2005, 42(4): 48-52.

2 J L Song, Q L Deng, C Y Chen, *et al*.. Rebuilding of metal components with laser cladding forming [J]. Applied Surface Science, 2006, 252(22): 7934-7940.

3 E Capello, D Colombo, B Previtali. Repairing of sintered tools using laser cladding by wire [J]. Materials Processing Technology, 2005, (164-165): 990-1000.

4 J Dutta Majumdar, A Pinkerton, Z Liu, *et al*.. Microstructure characterization and process optimization of laser assisted rapid fabrication of 316L stainless steel [J]. Applied Surface Science, 2005, 247(1): 320-327.

5 Dong Shiyun, Yan Shixing, Xu Binshi, *et al*.. Microstructure and mechanical property of NiCuFeBSi alloy with laser cladding on substrate of gray cast irons [J]. Chinese J Lasers, 2012, 39(12): 1203004.
董世运, 闫世兴, 徐滨士, 等. 铸铁件激光熔覆 NiCuFeBSi合金组织及力学性能[J]. 中国激光, 2012, 39(12): 1203004.

6 Pan Hu, Zhao Jianfeng, Liu Yunlei, *et al*.. Controllability research on dilution ratio of nickel-based superalloy by laser cladding reparation [J]. Chinese J Lasers, 2013, 40(4): 0403007.
潘 浒, 赵剑峰, 刘云雷, 等. 激光熔覆修复镍基高温合金稀释率的可控性研究[J]. 中国激光, 2013, 40(4): 0403007.
7 Zhang Ying, Lin Xin, Yang Gaolin, *et al*.. Structural characteristics of laser solid forming Zr-based bulk metallic glass [J]. Chinese J Lasers, 2013, 40(3): 0303005.
张 莹, 林 鑫, 杨高林, 等. 激光立体成形锆基块体非晶合金的组织特征[J]. 中国激光, 2013, 40(3): 0303005.
8 L Shepeleva, B Medres, W D Kaplan, *et al*.. Laser cladding of turbine blades [J]. Surface and Coatings Technology, 2000, 125(1): 45-48.
9 M L Zhong, W J Liu, G Q Ning, *et al*.. Laser direct manufacturing of tungsten nickel collimation component [J]. Materials Processing Technology, 2004, 147(2): 167-173.
10 Dong Ling, Yang Xichen, Zhang Haiming, *et al*.. Path generation for repairing damaged parts of free-form surfaces in laser remanufacturing [J]. Chinese J Lasers, 2012, 39(7): 0703007.
董 玲, 杨洗陈, 张海明, 等. 自由曲面破损零件激光再制造修复路径生成[J]. 中国激光, 2012, 39(7): 0703007.
11 C P Paul, A Jain, P Ganesh, *et al*.. Laser rapid manufacturing of Colmonoy-6 components [J]. Optics and Laser in Engineering, 2006, 44(10): 1096-1109.