Optimization of Direct Energy Deposition of 304L Stainless Steel through Laser Process Parameters

레이저 공정변수를 이용한 304L 스테인리스강 고에너지 직접 적층제조(DED) 최적화 연구

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Abstract

The quality of metal components manufactured by laser-based additive manufacturing technologies is governed by the process parameters. Moreover, the process parameters differ depending on the material used. In particular, direct energy deposition (DED) technology is vulnerable to the control of external environmental variables, and there are many process variables, such as powder characteristics and laser parameters, and thus many tests are required to determine the optimal parameters. In this study, an experiment was conducted to derive the conformity criterion of the DED process for metal powder (STS304L). First, the effects of laser energy output, laser header moving speed, powder feed rate, and gas feed rate on the DED process were studied. The experimental results showed that the deposition height decreased as the laser header moved faster and that the dilution ratio and the width of the heat-affected zone depended on the laser power and powder feed rate. Specimens were printed based on the process parameter values determined in the experiment, and tensile tests were conducted to analyze their mechanical performance.

Key Words: DED(Direct Energy Deposition), Additive manufacturing, Metal powder(STS304L), Laser process, dilution

1. Introduction

Additive manufacturing (AM) offers the economic benefit of no waste of unnecessary material and enabling complex shapes to be formed relatively easier, as compared to traditional subtractive manufacturing. Consequently, many studies have been conducted on applying AM as industrial manufacturing technique, while AM is already being applied to manufacture some products. Moreover, AM technology using various functional metallic materials is being actively researched owing to less material used and alloyability¹⁾.

Metal 3D printing techniques used for AM using metallic materials include powder bed fusion (PBF), binder

jetting, and direct energy deposition (DED). Of these, DED not only makes it easy to manufacture large parts, but it can also be easily integrated as tooling in machine tools, such as conventional machining center tooling (MCT). Accordingly, applied technologies are being developed in various industries, including die and mold, automotive, and aerospace²⁾. With fuel nozzles from GE Aviation, which began mass production using AM technique exclusively, the reliability of applying manufacturing technique using metal 3D printing has gradually increased within the industry. In particular, DED technique is used for partial tooling, not for outputting the entire product shape, but for partial repair of airplane parts or die/mold products³⁻⁶⁾.

Unlike other deposition methods, DED has a high un-

certainty for closure to external environment due to shielding by shield gas in the deposition sections where phase transition of the material takes place, while also being exposed to outside air. Moreover, the method of feeding the powder material to the melting pool is more dynamic than PBF or binder jetting and positional changes may occur according to the spatial movement of the tool and design shape. Therefore, because of many variable conditions, reliability and repeatability of printed products still need improvement. To determine the printing characteristics according to laser process parameters, which are limiting parameters of energy portion within the tooling part of DED, the present study experimentally evaluated the influence on tensile strength, which represents the mechanical properties and cross-sectional characteristics of printed products. The study aimed to use the findings to present laser process parameters for AM that are suitable for DED process and determine the influence on various metal powders through continued research to improve the mechanical performance of products manufactured via AM using DED technique.

2. Materials and Methods

2.1 Materials

The material used in the present study was stainless steel (STS304L; 45~150 μm in size) that was manufactured via gas atomization. STS304L is an ultra-low carbon steel, which has excellent intergranular corrosion resistance in welded state and high temperature strength. Accordingly, it is a material that is universally used for manufacturing parts that are difficult to heat treat, heat-resistant parts, and equipment in chemical, coal, and petroleum industries that require high intergranular corrosion resistance. The present study used such material with high utilization to investigate the deposition performance, meaning the cross-sectional character-

istics, according to the process parameters of laser AM. The chemical and physical properties of the metal powder used in the study were as shown in Tables 1 and 2 and Figures 1 and 2. The base used in the experiment was dissimilar carbon steel (S45C), which was $W100 \times D50 \times H10$ (mm) in size.

Fig. 1 SEM shape image of 45~150 μm the metal powder

Fig. 2 Particle size distribution of 45~150 μm the metal powder

Fig. 3 DED robot system(ROBOLASER)

Table 2 Physical characteristics of the metal powder

Type	Size(μm)	Apparent density (g/cm^3)	Flow rate (sec/50g)
STS304L	45~150	4.15	13.06

Table 1 Chemical composition of the STS304L metal powder(wt.%)

Elements	C	Mn	P	Si	Ni	Cr	Mo	S	Fe
Component specification	0.03	0.5	0.045	1.00	12.5~14	16~18	2.0~3.0	0.030	Bal
STS304L	0.019	0.1	0.02	0.83	13.1	17.2	2.05	0.030	Bal

Table 3 DED process parameter

Parameter \ Method	DED
Laser header moving speed	600, 900 mm/min
Laser output power	500, 700, 900 W
Powder feeding rate	3, 6 g/min
Carrier gas flow rate	2, 4, 6, 8 ℓ/min

2.2 Methods

The DED robot system shown in Fig. 3 (ROBOLASER, OR Laser, Germany) was used to conduct the deposition experiment using DED. The distance between the base and tool was set to 16 mm, which is the position of the focus. Meanwhile, the laser beam size was 1 mm. The other process parameters, as shown in Table 3, were 1070 nm range, laser output power, laser header moving speed, powder feeding rate, and carrier gas flow rate.

As shown in Fig. 4, the shape of the deposition model used in the experiment was designed to a size of W100 × D35 × H10 (mm), which was a suitable size to be used as tensile sample for the experiment on the evaluation of tensile strength, which is a mechanical performance indicator. SKM DCAM⁷⁾, a computer-aided manufacturing (CAM) software, was used for the tooling path for the sample model that had been designed and deposition process parameters were applied as shown in Table 4.

Fig. 4 Tensile strength part tool path used with SKM DCAM⁷⁾**Table 4** DED Process parameter of tensile strength part

Parameter \ Method	DED
Laser header moving speed	600 mm/min
Laser output power	700 W
Powder feeding rate	6 g/min
Carrier Gas flow rate	2 ℓ/min

Based on data derived from a previous experiment, the deposition process parameters for the tensile strength experiment sample were set to laser output power of 700 W, laser header moving speed of 600 mm/min, powder feeding rate of 6 g/min, and carrier gas flow rate of 2 ℓ/min in consideration of deposition time, efficiency, and minimal damage to the base material. The direction of deposition was designed relative to X-Y axes. To fabricate the sample for tensile strength testing that meets the ASTM E8/E8M standard, the deposition product was prepared to a size of W100 × D35 × H10 (mm). To increase the data reliability, three flat dog bone shaped samples were used to conduct tensile strength tests in a tensile test machine (ST1001, SALT, South Korea)⁸⁾.

For observation of the cross-sectional characteristics of the deposition product, the printed products were etched using 5% Nital etchant and cross-sectional imaging was performed using an optical microscope (IX70, OLYMPUS, Japan)⁹⁾.

3. Results and Discussion

3.1 Evaluation of deposition performance by laser header moving speed

For the evaluation, the experiment was conducted by altering the process parameters presented in Table 1 with tool moving speed, which is the actual machining speed, fixed at 600 and 900 mm/min. Fig. 3 shows the cross-sectional measurements for the experimental products.

The results of deposition experiment according to process parameters showed that deposition height increased as the powder feeding rate increased. Moreover, increase in laser output power showed increase in heat affected zone (HAZ) and dilution rate.

Fig. 4 shows the results of experiment performed with the laser header moving speed set to 900 mm/min and using the same process parameters. With respect to the influence of speed at different conditions, the results commonly showed clear decrease in deposition and HAZ heights as compared to the speed of 600 mm/min. However, changes in output energy and feeding gas tended to be similar at both speeds.

At powder feeding rate of 3 g/min, the appearance of cross-section that forms the melting pool appeared differently according to laser output power. At 500W, increase in gas feeding rate resulted in decreased deposition height and cross-sectional shapes with irregular dilution rate. It was determined that laser output power was lower than powder feeding rate. At 700W and 900W, deposition height decreased as the carrier gas flow rate increased, while dilution rate cross-sectional

shape appeared to be regular.

At powder feeding rate of 6 g/min, the results also showed that cross-sectional appearance varied according to laser output power. At 500W, the deposition cross section showed almost no dilution with the base material due to low output relative to powder feeding rate. Moreover, the deposition height tended to decrease from 2 l/min and above at 700W and from 4 l/min and above at 900W. In other words, when 900W was used, deposition efficiency was poor at carrier gas flow rate of ≥ 4 l/min.

3.2 Discussion of experiments according to deposition process parameters

Fig. 5 shows graphs of deposition heights of metal powder (STS304L) at laser header moving speed of 600 and 900 mm/min with varying deposition process parameters.

As shown in the figure, the deposition experiments according to process parameters showed that deposition height increased as the powder feeding rate increased. Increase in base material collision speed due to increase in flow rate and resulting increase in powder scattering caused decrease in the actual deposition height.

At 900 mm/min, the results for powder feeding rate of 3 and 6 g/min showed similar tendency as those of laser header moving speed of 600 mm/min, and overall, deposition height tended to decrease.

Fig. 7 shows the graphs of dilution rate of metal powder (STS304L) at laser header moving speed of 600 and 900 mm/min with varying deposition process parameters.

Dilution rate, which is defined as the mixture ratio between the base material and deposited metal powder, can be calculated by the equation shown below¹⁰⁾.

$$d = \frac{A_{mix}}{A_{mix} + A_c} \times 100\% \approx \frac{h_{mix}}{h_{mix} + h_c} \times 100\%. \quad (1)$$

Here, A_c is the upper deposition area of substrate surface; h_c is the height; w_c is the width; A_{mix} is lower mixed area of substrate surface; and h_{mix} is the height (Fig. 7).

Based on this, the present study showed the analysis results from substituting the cross-sectional analysis data according to varying deposition process parameters into Eq. (1).

Generally, low dilution rate is associated with failure of base material and deposition interface and quality degradation, whereas high dilution rate is associated with decrease in deposition rate relative to powder

(a) laser header moving speed : 600 mm/min, and powder feeding rate : 3 g/min

(b) laser header moving speed : 600 mm/min, and powder feeding rate : 6 g/min

(c) laser header moving speed : 900 mm/min, and powder feeding rate : 3 g/min

(d) laser header moving speed : 900 mm/min, and powder feeding rate : 6 g/min

Fig. 5 Cross-section of deposition by laser header moving speed and powder feeding rate

(a) laser header moving speed : 600 mm/min, and powder feeding rate : 3 g/min

(b) laser header moving speed : 600 mm/min, and powder feeding rate : 6 g/min

(c) laser header moving speed : 900 mm/min, and powder feeding rate : 3 g/min

(d) laser header moving speed : 900 mm/min, and powder feeding rate : 6 g/min

Fig. 6 Comparison of deposition height by Laser header moving speed and powder feeding rate

Fig. 7 Schematic view of the cross section of a clad track¹⁰⁾

feeding rate.

At powder feeding rate of 3 g/min and laser output power of 500W, dilution rate became more irregular with increase in carrier gas flow rate. At 700W and 900W, dilution rate tended to increase as carrier gas flow rate increased.

At powder feeding rate of 6 g/min, the carrier gas flow rate tended to increase up to 6 l/min and decreased at 8 l/min when the laser output power was set to 500W and 700W. When the laser output power was set to 900W, the dilution rate increased as the carrier gas flow rate increased, which was determined to be the result of powder feeding rate relative to output being low up to carrier gas flow rate of 9 l/min.

Accordingly, the most efficient parameters were determined to be powder feeding rate of 6 g/min, laser output power of 700W, and carrier gas flow rate of 2 l/min, which showed low dilution rate and high deposition height.

3.3 Results and discussion of experiments according to tensile strength part

The results from the tensile strength test showed approximately 624 MPa, which was slightly higher than 480 MPa of conventional casting product¹¹⁾. It was determined that such results were due to the fact that DED process involved repeated deposition, layer by layer, and had a relatively smaller melting pool than conventional casting products, and as a result, the mixture area of STS304L (austenite stainless steel) ferrous alloy (dilution) cooled faster, which in turn improved tensile strength due to formation of micro grains¹²⁾.

4. Conclusions

In the AM experiments on STS304L metal powder samples according to laser deposition process parameters, the influence of varying process parameters (laser output power, gas flow rate, powder feeding rate, and laser header moving speed) on the base and deposition was evaluated. The results were as follows:

(a) laser header moving speed : 600 mm/min, and powder feeding rate : 3 g/min

(b) laser header moving speed : 600 mm/min, and powder feeding rate : 6 g/min

(c) laser header moving speed : 900 mm/min, and powder feeding rate : 3 g/min

(d) laser header moving speed : 900 mm/min, and powder feeding rate : 6 g/min

Fig. 8 Comparison of dilution height by Laser header moving speed and powder feeding rate

Fig. 9 Fractured shape of tensile test coupons

Fig. 10 Fractured feature of tensile test coupons

1) In the experiment on the cross section of deposition samples according to laser output power, the results showed differences in deposition height and dilution rate. Considering the dilution rate and deposition height, 500W was found to be most efficient.

2) Deposition height increased as powder feeding rate increased, but with respect to deposition efficiency relative to powder feeding rate, low amount of powder consumed (6 g/min) was found to be suitable.

3) Deposition height decreased as carrier gas flow rate increased and deposition heights at 2~4 l/min were similar. Considering deposition efficiency, 2 l/min was determined to be the optimal condition.

4) In the comparison of deposition height according to laser header moving speed, powder feeding rate of 3 and 6 g/min showed similar tendencies, while the overall

deposition height tended to decrease as the moving speed increased.

5) Conventional STS304L casting products have a tensile strength of 480 MPa, while deposition products manufactured by metal 3D printing using DED technique showed a higher tensile strength of 624 MPa.

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Optimization of Direct Energy Deposition of 304L Stainless Steel through Laser Process Parameters

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1. 서 론

적층 제조(AM: additive manufacturing)는 전통적 절삭가공보다 복잡한 형상을 쉽게 제작할 수 있고, 형상품의 불필요한 소재 소모가 없는 경제성의 이점 때문에 산업용 제조 기술로의 적용 연구가 상당수 진행되었으며 실용 기술로 활용되어 제품 제조에 일부 적용이 시작되었다. 또한 소재 소모가 적고 합금 용이성 때문에 다양한 기능성 금속 소재를 사용한 적층 제조 기술 연구가 활발히 진행되고 있다¹⁾.

금속 소재를 이용한 적층 제조에 활용되는 금속 3D 프린팅 기술에는 PBF(Powder Bed Fusion), Binder jetting 방식 및 DED(Direct Energy Deposition) 등 여러 가지가 있지만 그중 DED의 경우 대형부품 제작에 용이할 뿐만 아니라 기존 MCT(Machining Center Tooling)와 같은 공작기계에 툴링 형태로 접목이 용이하여 실용화 기술 분야로 금형, 자동차, 우주항공 등 전방위 산업 분야에 적용 기술 개발이 진행되고 있다²⁾. AM기술을 전적으로 이용하여 양산을 시작한 GE Aviation의 Fuel Nozzle을 통해 산업계에서도 차츰 금속 3D 프린팅의 제조 기술 적용에 신뢰성이 높아지고 있으며, 특히 DED 공법의 경우 항공기 부품, 금형 제품의 부분 보수 등에 제품 형상 전체 출력이 아닌 부

분 툴링으로 적용되고 있다³⁻⁶⁾.

하지만 다른 적층 공법과 달리 DED는 외기에 노출되면서도 동시에 소재의 상변화가 발생하는 적층 구간이 쉴드 가스에 의한 차폐로 외부 환경에 대한 폐쇄에 불확실성이 높고, 공급 분말 소재가 멜팅풀에 공급되는 방식도 PBF나 binder jetting 방식에 비해 동적이어서 툴의 공간이동과 디자인 형상에 따라 자세변화가 발생하는 등 변수 조건이 많아 출력물의 신뢰성 및 반복 재현성에 대한 개선을 여전히 필요로 한다. 본 연구에서는 DED의 툴링 부분 중 에너지 영역의 제어 변수인 레이저 공정변수에 따른 출력 특성을 규명하기 위해 출력물의 단면 특성과 기계적 성질을 대표하는 인장강도의 영향성을 실험적으로 평가하였다. 이를 통해 DED 공정에 적합한 적층제조용 레이저 공정 변수를 제시하고, 지속적인 연구를 통해 다양한 금속분말에서의 영향성을 규명함으로써, DED 공법을 통한 적층 제조물의 기계적 성능을 개선해 나가고자 한다.

2. 실험 재료 및 방법

2.1 실험 재료

본 연구에서 사용된 소재는 가스분사 방식으로 제조된 45~150 μm 크기의 스테인리스강(STS304L)을 사용하였다. STS304L은 극저탄소강으로 고온강도 및

Table 1 Chemical composition of the STS304L metal powder(wt.%)

Elements	C	Mn	P	Si	Ni	Cr	Mo	S	Fe
Component specification	0.03	0.5	0.045	1.00	12.5~14	16~18	2.0~3.0	0.030	Bal
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Table 2 Physical characteristics of the metal powder

Type	Size(μm)	Apparent density (g/cm^3)	Flow rate (sec/50g)
STS304L	45~150	4.15	13.06

Fig. 1 SEM shape image of 45~150 μm the metal powder

Fig. 2 Particle size distribution of 45~150 μm the metal powder

용접한 상태에서 내입계 내식성이 우수하여 내입계부식성이 높게 요구되는 화학, 석탄, 석유산업기기 및 내열 부품과 열처리가 곤란한 부품제조에 보편적으로 사용되는 소재이다. 이러한 활용성 높은 소재를 이용하여 본 연구에서는 레이저 적층제조 공정변수에 따른 적층 성능, 즉 단면 특성을 알아보고자 한다. 사용된 금속분말의 화학적, 물리적 특성은 Table 1, 2 및 Fig. 1, 2에 나타내었다. 실험에 사용된 기저부는 이중인 탄소강(S45C)

Fig. 4 Tensile strength part tool path used with SKM DCAM⁷⁾

을 사용하였고, 크기는 W100 × D50 × H10 (mm)이다.

2.2 실험 방법

Fig. 3에서 보여지는 직접용착적층 로봇 장치(DED Robot System, ROBOLASER, OR Laser, 독일)를 사용하여 DED 적층 실험을 수행하였다. 기저부와 틀과의 거리는 포커스 위치인 16 mm로 고정시켰으며, 이 때 레이저 빔 사이즈는 1 mm이다. 그 외에 나머지 공정변수는 1070nm 대역의 레이저 출력(Laser output power)과 레이저 조사빔의 이동속도(Laser header moving speed), 분말 공급량(Powder feeding rate), 송급 가스 유량(Carrier gas flow rate)이며, 각각 공정변수는 Table 3에 나타 내었다.

실험에서 적층할 모델 형상은 기계적 성능 지표인 인장강도 평가 실험을 위해 인장 시편을 만들 수 있는 크기로 설정하여 Fig. 4와 같이 W100 × D35 × H10 (mm)로 디자인하였다. 디자인된 시편 모델에 대한 툴링 경로는 CAM(Computer-Aided Manufacturing) 소프트웨어 인 SKM DCAM⁷⁾를 사용하였으며, 적층공정 파라미터는 Table 4와 같이 적용하였다.

인장 강도 부품에 적층 공정변수는 앞 실험에서 도출

Fig. 3 DED robot system(ROBOLASER)

Table 3 DED process parameter

Parameter	Method	DED
Laser header moving speed		600, 900 mm/min
Laser output power		500, 700, 900 W
Powder feeding rate		3, 6 g/min
Carrier gas flow rate		2, 4, 6, 8 ℓ/min

Table 4 DED Process parameter of tensile strength part

Parameter	Method	DED
Laser header moving speed		600 mm/min
Laser output power		700 W
Powder feeding rate		6 g/min
Carrier Gas flow rate		2 ℓ/min

된 데이터를 바탕으로 적층 시간, 효율, 모재 손상을 최소화하는 레이저 출력(700 W), 레이저 조사빔의 이동속도(600 mm/min), 분말 공급량(6 g/min), 송급 가스 유량(2ℓ/min)을 설정하였으며, 적층 방향은 X-Y 축을 기준으로 제작 하였다. 인장 시편은 ASTM E8/E8M에 규정에 적합한 시편으로 가공하여 사용하기 위해 적층 결과물의 크기를 W100 × D35 × H10(mm)로 제작 하였다. 또한, 데이터 신뢰성을 높이기 위해 flat dog bone shape 시편 3개를 이용하여 인장 시험기(ST1001, SALT, 한국)에서 인장 실험을 수행하였다⁸⁾.

적층된 결과물의 단면 특성을 관찰하기 위해 출력된 가공물은 Nital 5%를 사용하여 에칭을 한 후 광학현미경(IX70, OLYMPUS, 일본)으로 단면을 촬영하였다⁹⁾.

3. 실험 결과 및 고찰

3.1 레이저 조사빔의 이동속도별 적층성능 평가

실험 평가는 가공 속도인 톨 이동속도(Moving speed)를 600과 900 mm/min으로 고정하고 Table 1에서 제시한 공정변수를 변화시키면서 실험을 수행하였으며 Fig. 3은 실험 결과물에 대한 단면 측정 결과이다.

실험 결과를 보면 공정변수에 따른 적층 실험에서는 분말 공급량이 증가할수록 적층 높이가 높아지는 것을 확인할 수 있다. 또한 레이저 출력 증가는 열영향부 및 회석률의 높이가 증가하는 것을 확인할 수 있다.

두번째 속도 설정인 레이저 조사빔의 이동속도 900 mm/min에서의 동일 공정 변수별 실험 수행 결과는 Fig. 4와 같다. 조건별 속도 영향을 보면 공통적으로 속도 600 mm/min에 비해 적층 높이 및 열영향부 높이가 감소하는 것을 뚜렷하게 관찰할 수 있었다. 하지만 출력 에너지와 공급 가스 변화에는 두 속도 모두 비슷한 경향이 나타나는 것을 확인할 수 있다.

분말 공급량 3g/min의 경우 레이저 출력에 따른 용융풀이 형성되는 단면 형상이 상이하게 나온 것을 볼 수 있다. 500W의 경우 가스 공급 속도가 증가할수록

적층 높이가 감소하며 불규칙적인 회석률 단면 형상이 발생 하였으며, 이는 분말 공급량에 비해 레이저 출력이 낮은 것으로 판단된다. 700W와 900W 경우 적층 높이는 송급 가스 유량 속도가 증가 할수록 감소하였으며, 회석률 단면 형상은 균일한 형상이 나타나는 것을 볼 수 있다.

분말 공급량 6g/min의 경우도 마찬가지로 레이저 출력에 따른 단면 형상이 상이하게 나온 것을 볼 수 있다. 500W 경우 분말 공급량 대비 출력이 낮아 모재와 회석이 거의 이루어지지 않은 것을 적층 단면 형상을 볼 수 있다. 700W는 2ℓ/min 이상부터는 적층 높이가 감소하는 경향을 보였으며, 900W는 4ℓ/min 이상에서는 적층 높이가 감소하는 경향을 보였다. 즉 900W 경우에는 송급 가스 유량이 4ℓ/min 이상에는 적층 효율이 좋지 않을 것을 알 수 있다.

3.2 적층 공정 변수에 따른 실험 고찰

먼저, 금속분말(STS304L)에 대한 적층 공정 변수에 따른 레이저 조사빔의 이동속도 600, 900 mm/min에 대한 적층 높이를 Fig. 5에 그래프로 나타내었다.

그림에서 보듯이 공정변수에 따른 적층 실험에서는 분말 공급량이 증가 할수록 적층 높이가 높아지는 것을 확인할 수 있으며, 유속 증가에 따른 분말의 모재 충돌 속도 증가 및 이로 인한 분말 산란 증가로 실제 적층 높이가 감소하는 것을 알 수 있다.

900 mm/min 경우 분말 공급량 3, 6g/min에서 레이저 조사빔의 이동속도 600 mm/min과 비슷한 경향성을 보였으며, 전체적으로 적층 높이가 감소하는 경향을 볼 수 있다.

금속분말(STS304L)에 대한 적층 공정 변수에 따른 레이저 조사빔의 이동속도 600, 900 mm/min에 대한 회석률을 Fig. 7에 그래프로 나타내었다.

회석률은 모재와 적층된 금속분말 사이의 혼합 비율로 정의되며, 다음 식과 같이 정의된다¹⁰⁾.

$$d = \frac{A_{mix}}{A_{mix} + A_c} \times 100\% \approx \frac{h_{mix}}{h_{mix} + h_c} \times 100\%. \quad (1)$$

여기서, A_c : 기판 표면 상부 적층 면적, h_c : 높이, w_c : 폭, A_{mix} : 기판 표면 하부 혼합 면적, h_{mix} : 높이를 나타낸다. (Fig. 7)

이를 바탕으로 본 연구에서는 적층 공정 파라미터 변화에 따른 단면 분석 데이터를 식(1)에 도입하여 분석한 결과를 나타내었다.

일반적으로 회석률이 낮으면 모재와 적층 계면부 탈

(a) laser header moving speed : 600 mm/min, and powder feeding rate : 3 g/min

(b) laser header moving speed : 600 mm/min, and powder feeding rate : 6 g/min

(c) laser header moving speed : 900 mm/min, and powder feeding rate : 3 g/min

(d) laser header moving speed : 900 mm/min, and powder feeding rate : 6 g/min

Fig. 5 Cross-section of deposition by laser header moving speed and powder feeding rate

(a) laser header moving speed : 600 mm/min, and powder feeding rate : 3 g/min

(b) laser header moving speed : 600 mm/min, and powder feeding rate : 6 g/min

(c) laser header moving speed : 900 mm/min, and powder feeding rate : 3 g/min

(d) laser header moving speed : 900 mm/min, and powder feeding rate : 6 g/min

Fig. 6 Comparison of deposition height by Laser header moving speed and powder feeding rate

Fig. 7 Schematic view of the cross section of a clad track¹⁰⁾

락 및 품질이 저하되고, 희석률이 높으면 분말 공급량 대비 적층율이 감소하게 된다.

분말 공급량 3g/min와 레이저 출력 500W의 경우 송급 가스 유량이 증가할수록 불규칙적인 희석률을 보여주며, 700W와 900W 경우 송급 가스 유량 증가할수록 희석률이 증가하는 것을 볼 수 있다.

분말 공급량 6g/min의 경우에 레이저 출력 500W와 700W의 경우 송급 가스 유량이 6ℓ/min까지 증가하다 8ℓ/min에서 감소하는 경향을 볼 수 있다. 900W의 경우 송급 가스 유량이 증가 할수록 희석률도 증가

하는 것을 볼 수 있으며, 이는 송급 가스 유량 9ℓ/min까지는 출력 대비 분말 공급량이 낮은 것으로 판단된다.

여기서, 희석률이 낮으며, 적층높이가 높은 분말 공급량 6g/min, 레이저 출력 700W, 송급 가스 유량 2ℓ/min 파라미터가 가장 효율적이라고 판단된다.

3.3 인장 강도 부품에 따른 실험 결과 및 고찰

인장 시험에 대한 결과는 기존 주조 제품의 인장 값인 480 MPa 보다 높은 약 624 MPa 값을 얻을 수 있었다¹¹⁾. 이는, 기존 주조 제품에 비해 DED 공정은 한층씩 적층을 반복하며 상대적으로 작은 멜팅풀 사이즈 때문에 STS304L(오스테나이트계 스테인리스강) 철계 합금의 혼합 면적(Dilution)이 빨리 냉각되고, 이로 인한 미세화된 결정립 생성에 의해 인장강도가 향상된 것으로 판단된다¹²⁾.

4. 결 론

레이저 적층 공정변수에 따른 STS304L 금속분말

Fig. 8 Comparison of dilution height by Laser header moving speed and powder feeding rate

Fig. 9 Fractured shape of tensile test coupons

Fig. 10 Fractured feature of tensile test coupons

적층 제조 실험 결과, 공정 변수(레이저 출력, 가스 공급량, 분말 공급량, 레이저 조사빔의 이동속도) 변화가 기저부와 적층에 미치는 영향을 평가한 결과는 다음과 같다.

1) 레이저 출력에 따라 적층 샘플 단면에서 적층 높이 및 희석률 차이가 나타났으며, 희석률과 적층 높이를 고려한다면 500W가 가장 효율적이다.

2) 분말 공급량이 증가할수록 적층 높이가 증가하였지만 분말 투입 대비 적층효율 측면에서는 분말 소모량이 적은 6g/min가 적합하였다.

3) 송급 가스 유량이 증가할수록 적층 높이 감소하였으며, 2~4ℓ/min의 적층 높이가 비슷하였고, 적층 효율을 감안한다면 2ℓ/min가 최적의 조건이라고 판단된다.

4) 레이저 조사빔의 이동속도에 따른 적층높이 비교 시 분말 공급량이 3, 6g/min의 경우 비슷한 경향성을 보였으며, 이동속도가 빠를수록 전체적인 적층 높이는 감소하는 경향을 보인다.

5) 기존 STS304L 주조 제품의 인장 강도는 480 MPa를 제시하고 있으며, DED 방식의 금속 3D 프린터로 제작된 적층 결과물에 인장강도는 624 MPa로 보다 높은 인장강도를 얻을 수 있었다.

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