Laser Metal Deposition Repair Applications for Ti-6Al-4V Alloy

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DOI **10.13140/RG.2.2.35949.38889**

Keywords: Laser Metal Deposition, Ti-6Al-4V powder and substrate, Taguchi L9 Orthogonal array method, Process parameters.

ABSTRACT. Laser metal deposition is an additive manufacturing process, which is used to produce functional metal parts or repair existing parts. This paper focuses on deposition of Ti-6Al-4V material for remanufacturing of existing Ti-6Al-4V components. Optimization of laser metal deposition process parameters is significant in achieving good metallurgical and mechanical properties such as fine grain structure and bonding strength for aerospace applications. Taguchi's L9 orthogonal array method has been adopted to optimize the laser power, powder feed rate and scan speed. Analysis of variance (ANOVA) is used to study the effect of process parameters on the deposit and verification trial experiments were conducted to ascertain the optimum process parameters performance. Residual stress measurement results revealed that the residual stress is compressive and significantly higher in optimized test specimen with good bonding strength. The optimized results shown that enhanced properties in refurbishment of aero engine parts using Ti-6Al-4V powder material.

Introduction: Laser Metal Deposition (LMD) is an additive manufacturing process, which builds 3 dimensional parts directly from CAD data. A high power laser heat source is used to create a melt pool in the substrate and powder material is fed co-axially in to the melt pool. Due to rapid cooling the molten pool solidification takes place to produce highly dense metal parts with reduced waste of material compared to conventional manufacturing process.

[1] LMD is a latest technology, which is used for freeform fabrication and repair of engineering and aerospace components [2]. Kamran shah et.al [3] have studied the effects of process parameters on direct laser metal deposition of IN 718 on Ti-6Al-4V substrate by using pulsed laser heat source parameters. It was found that optimized process parameters like laser power, scanning speed and powder feed rate resulted in crack free deposition with improved mechanical and metallurgical properties. Dinda et al. [4] have investigated microstructure analysis and thermal properties of Inconel 625 process with direct metal deposition. In this study Taguchi L9 orthogonal array method was applied to evaluate the effect of process parameters on the microstructure and mechanical properties of Inconel 625 material. Ryan Cottam et al. [5] studied the laser cladding of Ti-6Al-4V powder to understand the effect of laser cladding parameters on the metallurgical properties of the material. It was observed that microstructure of Ti-6Al-4V deposit in the clad zone with optimized process parameters was refined and contributed to the good deposition strength. Qun-li et al. [6] have studied direct laser metal deposition of Inconel-718 and the effects of process parameters on rate of deposition and layer thickness. It was found that the optimized process parameters lead to directional solidification with fine martensite microstructure and increased microhardness. R. Keshavamurthy et al. [2] have carried out process parameters optimization for direct metal deposition of H13 tool steel by using Taguchi orthogonal array method of design of experiments. The effect of powder feed rate, laser scan speed

and laser power on the hardness of the deposit have been studied. It was found that optimum process parameters have contributed to the increased hardness of the deposit and the optimised process parameters were verified from the analysis of variance (ANOVA). Laser Metal Deposition process includes several process parameters such as laser power, scan speed, beam diameter, powder feed rate, hatch spacing, layer thickness and scanning orientation.

From the above literature review, it is crucial to optimize these process parameters to achieve the desired quality characteristics of the deposited materials. In view of above, the objective of the current study is to optimize the process parameters of laser metal deposition of Ti-6Al-4V powder on Ti-6Al-4V substrate using Taguchi L9 orthogonal array method to achieve maximum hardness and bonding strength. Ti-6Al-4V is having high strength to weight ratio widely used in aerospace applications such as airframe, compressor blades, vanes and discs at elevated temperature.

Details of Experiments: *Deposition material***:** Fig.1 shows the scanning electron microscope (SEM) of Ti-6Al-4V powder particles used in the current study. As shown in the Fig.1 the powder particles are spherical in shape and size distribution varies between 44-106 μm and the powders produced by gas atomization process. Fig.2 shows the EDS analysis of elemental composition of Ti-6Al-4V material. Table-1 shows the chemical composition of Ti-6Al-4V powder material used in the present study.

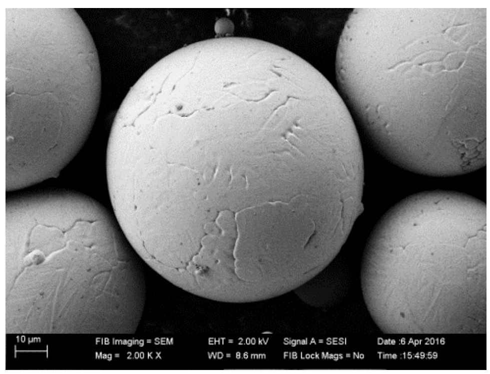


Fig. 1. Scanning electron micrograph of Ti-6Al-4V powder at 2000 X Magnification.

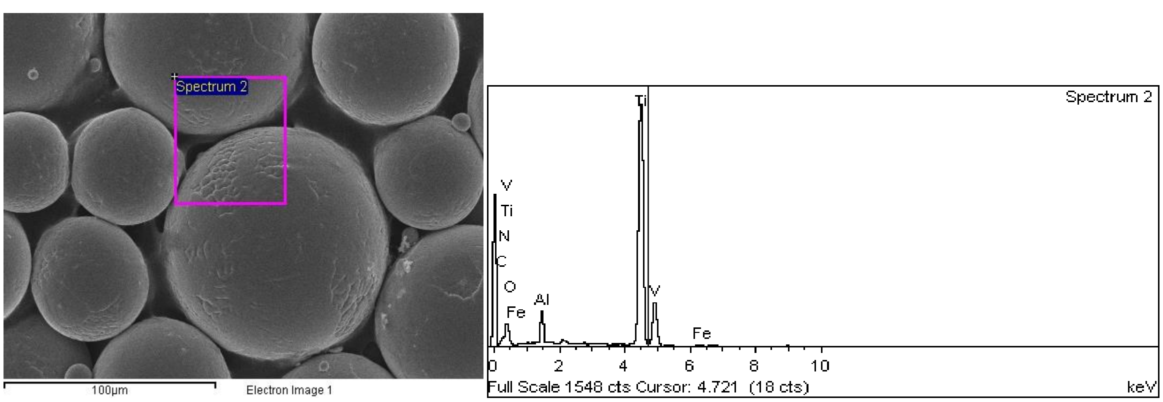


Fig. 2. SEM image and EDAX pattern of elemental composition.

Table 1. Chemical composition of Ti-6Al-4V powder

Element	C	O	N	H	Fe	Al	V	Ti
Percentage	0.01	0.063	0.02	0.0045	0.21	6.4	4.0	Balance

Substrate material: The substrate material used in the present study is Ti-6Al-4V plate to deposit Ti-6Al-4V powder. The chemical composition of Ti-6Al-4V substrate is given in the Table. 2.

Table 2. Chemical composition of Ti-6Al-4V substrate

Element	C	Al	Ti	V	Fe
Percentage	0.0590	5.6600	90.2100	3.7200	0.1400

Planning of experiments: Using Taguchi method experiments are planned since it is a robust design method when the process is affected by several process parameters. When compared with traditional methods of experimental planning, Taguchi method helps in reducing number of experiments, cost and time. Taguchi suggested orthogonal array method, which gives different combinations of parameters and their levels for each set of experiment [7, 8]. As per Taguchi orthogonal array method complete process parameter area is investigated with least number of experiments.

Design of experiments using Taguchi L9 Orthogonal array method: In the present study the best potential combination of process parameters have been determined by using Taguchi L9 orthogonal array method. Laser power, scan speed and powder feed rate have been selected as variable input process parameters and higher hardness as the desired output and quality characteristic. L9 orthogonal arrays and signal to noise (*S*/*N*) ratio are the two important tools used in Taguchi design of experiments method. The column of L9 orthogonal array represents the process parameters to optimize and the rows represents the levels of each process parameter. The mean and the variance of the output response at every parameter setting in L9 orthogonal array are later combined in to a single performance measure known as *S*/*N* ratio and the *S*/*N* ratio helps to measure quality characteristics with importance on variation [9, 10]. Minitab software (Version: 17) was used to calculate the *S*/*N* ratio using Taguchi method. Input process parameters for laser metal deposition of and their levels are shown in table. 3 and experimental plan based on Taguchi L9 orthogonal array method is shown in table. 4.

In the present research work the maximum power efficiency of the Laser Metal Deposition Machine – TRUMPF LASER CELL 1005 is 4000W. We have selected the intermediate Laser Power 2500 W, Scanning Speed 600mm/min and beam dia of 3 mm. From these parameters we have found the energy density energy $\mathcal{E}_d$ = 83.33 J/mm^2 using equation (1) for good quality of deposition, which is in the workable range based on review of literature.

$$\mathcal{E}_d = \frac{60 \times \mathrm{P}}{\mathrm{d} \times \mathrm{V}} \quad \mathrm{J/mm^2} \qquad (1)$$

where *P* – is the laser power;

V – is the scanning speed or velocity;

D – is the laser beam diameter [11].

Using the energy density $\mathcal{E}_d$ = 83.33 J/mm^2 we have designed the experiment using Taguchi's L9 Orthogonal Array with 3 factors and 3 levels. From the design of experiments result we have selected the optimum parameters to build the test specimens.

Table 3. Input process parameters and levels.

Sl No.	Parameters	Level		
		Level 1	Level 2	Level 3
1	Laser power (W)	2350	2500	2650
2	Laser scan speed (mm/min)	500	600	700
3	Powder feed rate (g/min)	3	4	5

Table 4. Experimental plan based on Taguchi L9 orthogonal array.

Expt. No.	Powder Feed Rate (g/min)	Laser Power (W)	Scan Speed (mm/min)
1	4	2350	600
2	4	2500	700
3	4	2650	500
4	3	2350	500
5	3	2500	600
6	3	2650	700
7	5	2350	700
8	5	2500	500
9	5	2650	600

Laser Metal Deposition: Laser Metal Deposition of Ti-6Al-4V on Ti-6Al-4V substrate was carried out using TRUMPF LASER CELL LMD system with 4000W CO_2 laser with laser beam diameter of 3mm. The deposition was carried out in argon-controlled atmosphere to avoid oxidation. Test specimens were prepared with two layer depositions with 1.2 mm layer thickness and 10 x 30 mm size as shown in Fig.3.

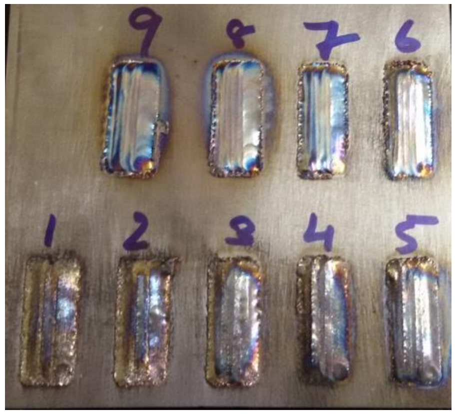


Fig. 3. Ti-6Al-4V deposition on Ti-6Al-4V substrate as per L9 orthogonal array.

After deposition the samples were held in a fixture on SODICK A350 Mark 21 submerge type wire electric discharge machine (EDM) and cut in transverse direction using brass wire (dia 25μm) as a tool electrode. The sectioned samples were polished with three coarse grits (600, 800 and 1200) and final polishing media with 0.05 microns alumina powder. The polished Ti-6Al-4V samples were etched using a mixture of 8 gms KoH (Potassium Hydroxide), 10 ml H_2O_2 (Hydrogen Peroxide), 60 ml distilled water and it is immersed for about 20 seconds to reveal the microstructure details. Microstructure studies were carried out on metallographically polished surfaces using optical microscope of make: Nikon, Japan and model: Eclipse LV 150. Microhardness tests were conducted using Vickers microhardness tester of make: CLEMEX, Canada and the indentation was measured using CLEMEX vision PE image analyzer software. Indentations were made at 5 locations on the substrate and deposit from the interface, using a load of 100 *gms* for duration of 10 seconds. Hardness value of each sample is a result of the average of all five measured readings.

Results and discussions: *Microstructure:* Fig.4 shows the microstructure of Ti-6Al-4V deposit on Ti-6Al-4V substrate. The microstructural analysis is the function of combined effect of laser power, scan speed and powder feed rate, which is depicted by using the series of optical microscope images as shown in the Fig. 4. All the images are viewed at 200X magnification. It is observed that the microstructure comprises of combination of acicular α phase (martensite) and Widmanstatten structure. Sample 7 shows that the amount of acicular α phase is more when compared to other images, which have resulted from higher, scan speed; powder feed rate and less laser power. Further, the sample 7 exhibited more hardness as reported in table. 6 due to rapid cooling of the melt pool, which resulted in formation of acicular α, phase and in general produces the α martensite microstructure [12]. This combination is imparting the better cooling effect to have acicular α phase (martensite phase). Further, all the sample reveals least porosities and no evident cracks or incoherence exists.

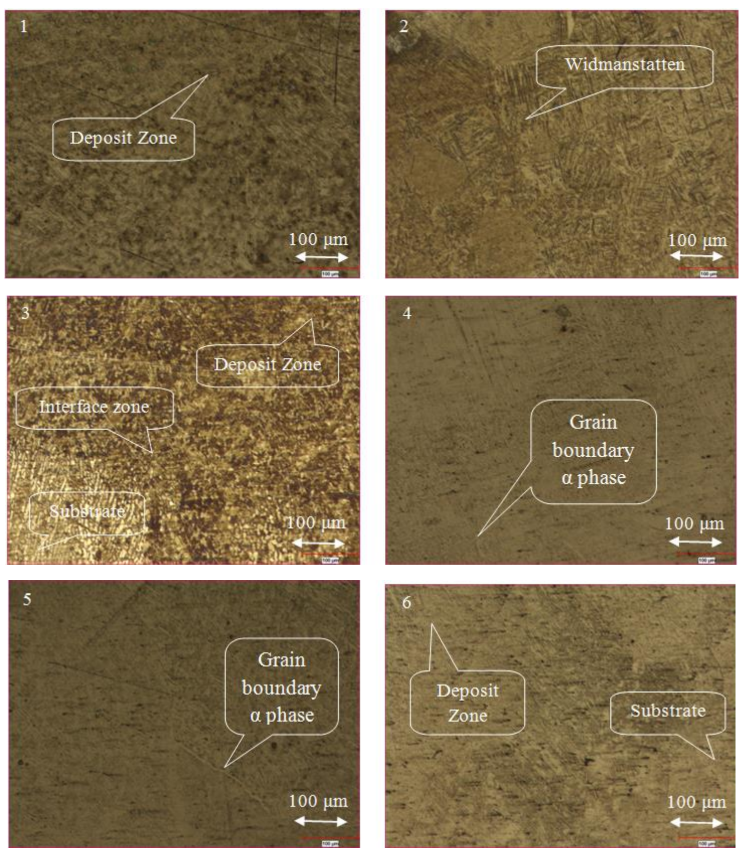
Hardness: Table. 5 shows the hardness values of Ti-6Al-4V deposit. The minimum and maximum hardness of the samples obtained are 407.12 and 459.54 HV for the experimental samples 7 & 3 correspondingly. The fine grain size and minimum porosity attributes to the higher hardness and strength of the material. The presence of interstitial atoms and the density dislocations decides the free plastic deformation of the material, thereby improving the resistance to plastic deformation, which leads to higher hardness. [2, 13].

Analysis of S/N ratio: In the current study, hardness was considered as the quality characteristic for laser metal deposition technology. Higher value of hardness is suitable for deposition of Ti-6Al-4V; therefore, the concept of "larger-the-better" is adopted for optimization of process parameters by Taguchi L9 orthogonal array method.

Table 5. Hardness and S/N values for Taguchi L9 experiments.

Expt. No.	Microhardness (HV)	S/N ratio
1	407.12	52.1944
2	436.27	52.7951
3	413.47	52.3289
4	420.80	52.4815
5	410.39	52.2639
6	442.11	52.9106
7	459.54	53.2465
8	436.04	52.7905
9	434.22	52.7542

As shown in the above table the best performance of the process is indicated by a higher value of S/N (Larger is better). Hence, the optimum level of the process parameters is the level of the highest S/N value.



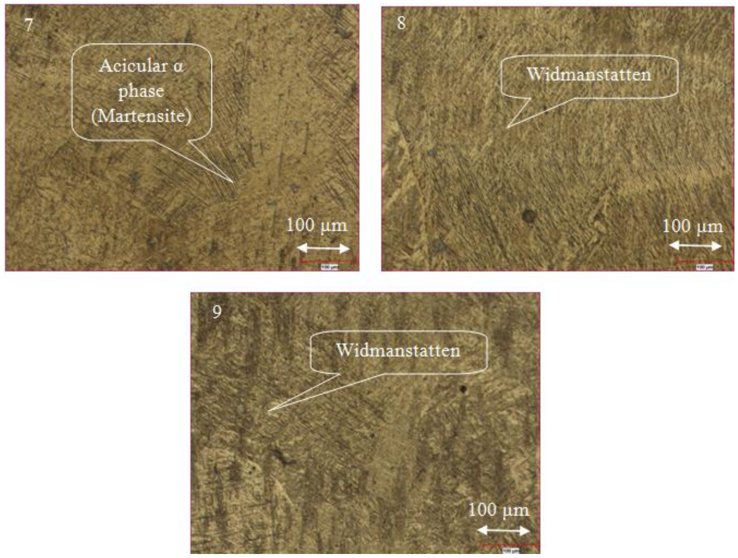


Fig. 4. Optical micrographs of Ti-6Al-4V deposits as per Taguchi's L9 orthogonal array.

(1) 2350 W, 600 mm/min, 4 g/min; (2) 2500 W, 700 mm/min, 4 g/min; (3) 2650 W, 500 mm/min, 4 g/min; (4) 2350 W, 500 mm/min, 3 g/min; (5) 2500 W, 600 mm/min, 3 g/min; (6) 2650 W, 700 mm/min, 3 g/min; (7) 2350 W, 700 mm/min, 5 g/min; (8) 2350 W, 500 mm/min, 5 g/min; (9) 2650 W, 600mm/min, 5 g/min.

Powder feed rate: The effect of powder feed rate on hardness is attributed from the Fig.5 that the S/N ratio is decreasing with increase in powder feed rate up to 4 g/min and then S/N ratio is increasing with the further increase in powder feed rate at 5 g/min. Hence the optimum powder feed rate is 5 g/min.

Laser power: The effect of laser power on hardness is as shown in the Fig5. It is observed that the S/N ratio is increasing with increase in laser power. This shows that the optimum laser power is 2650 W.

Scanning speed: The effect of laser scanning speed on hardness is shown in the Fig.5. It is observed that S/N ratio is increasing with increase in scanning speed. This shows that the optimum scan speed is 700 mm/min.

Based on the analysis of the S/N ratio, the optimized process parameters for achieving maximum hardness are powder feed rate: 5 g/min, laser power: 2650 W, Laser scanning speed: 700 mm/min.

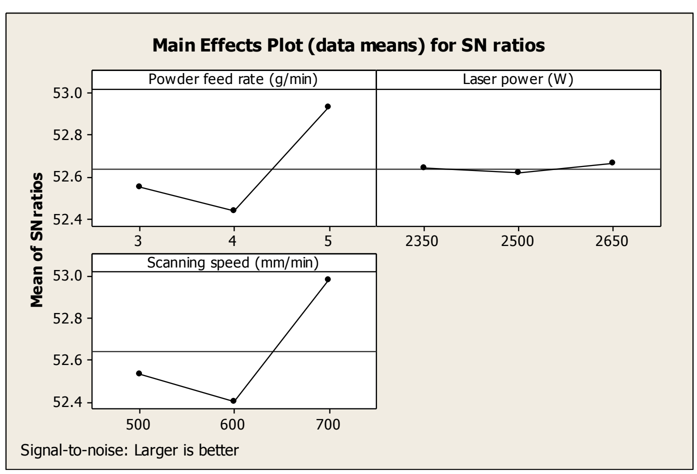


Fig. 5. Main Effects Plot for SN ratios.

Analysis of Variance (ANOVA): The process parameters importance has been studied by analysis of variance for S/N ratio. Based on analysis of variance, each parameter contribution has been quantified under column F of Table. 6. From table 6 it clearly reveals that the F value for scan speed is very high when compared to laser power and powder feed rate. This is a clear indication that the influence of scan speed is significantly larger than the influence of laser power and powder feed rate for achieving higher hardness.

Table 6. Analysis of variance for S/N ratio

Source	Degrees of freedom (DOF)	Sum of squares	Mean square	F – ratio (F)	P – ratio (P)
Powder feed rate	2	0.36984	0.19842	61.42	0.016
Laser power	2	0.00346	0.00173	0.54	0.651
Scan speed	2	0.55588	0.27794	86.04	0.011
Error	2	0.00646	0.00323		
Total	8	0.96264			

Optimized process parameter verification test: A design of experiments verification test has been carried out for laser metal deposition of two layers of Ti6Al4V on Ti6Al4V substrate under optimized process parameters to study the hardness. The obtained deposition hardness under optimized condition is 461.22 HV as shown in table. 7. It is noticed that the hardness value of the optimized condition is considerably higher than that of the deposition experiments carried out corresponding to L9 orthogonal array. The optimized sample was deposited using 2650 W laser power, 700 mm/min scan speed and 5 g/min powder feed rate. It clearly reveals that fine and consistent 'α martensite' microstructure may attributes to the higher hardness as shown in Fig. 6.

Table 7.Optimized process parameters and Hardness.

Expt. No.	Laser Power (W)	Powder flow rate (g/min)	Laser scan speed (mm/min)	Hardness (HV)
1	2650	5	700	461.22

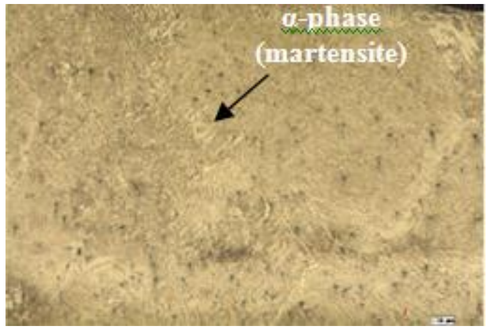
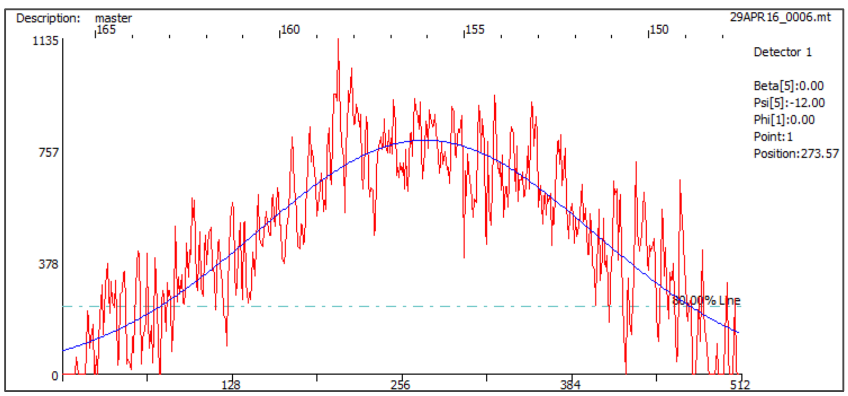
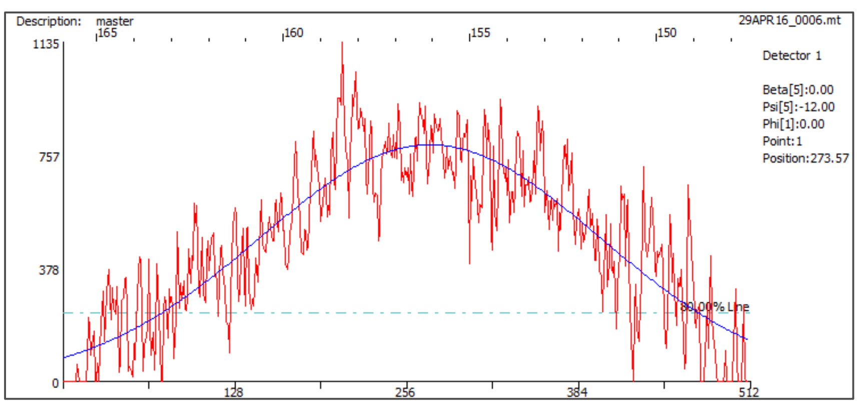


Fig. 6. Optical micrograph of Ti-6Al-4V deposit under optimum process parameter.

Residual Stresses: Residual stress was measured using X-ray diffraction method. The X-ray diffraction pattern shown in Fig. 7 (a) & (b) reveals the residual stress result of Ti-6Al-4V deposits. Residual stress measurement has carried out on L9 test specimen and optimized test specimen of Ti-6Al-4V deposit. It is observed that the residual stress is compressive in both L9 and optimized Ti-6Al-4V specimens. The measured residual stress in L9 test specimen is -153.3 ± 21.3 MPa and -277.8 ± 20.2 MPa in optimized test specimen. This shows that the residual stress in optimized Ti-6Al-4V test specimen is significantly higher with good bonding strength.



(a)



(b)

Fig. 7. Ti-6Al-4V diffraction pattern (a) L9 test specimen 1 (b) optimized test specimen.

Summary. Process parameters for laser metal deposition of Ti-6Al-4V were optimized using Taguchi L9 orthogonal array method. The optimum process parameters are found to be laser power: 2650 W, powder feed rate: 5 g/min and scan speed: 700 mm/min. The optimum process parameters have been confirmed by the verification experiment conducted. X-ray Diffraction residual stress studies clearly reveal that the residual stress is compressive and significantly higher in parts deposited under optimum laser power, laser scan speed and powder feed rate. The obtained results from the optimization of process parameters could be directly used to repair complex aero engine Ti-6Al-4V parts.

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