Surface micro-cracks and microstructures of Ti6Al4V alloy fabricated by high-layer thickness multi-laser directed energy deposition additive manufacturing process

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Abstract: Implementing a high-layer thickness additive manufacturing (AM) can significantly reduce the manufacturing time. With this, the cracking phenomenon and microstructure of the additively manufactured parts should be controlled. This paper investigates the surface micro-cracks and microstructures of Ti6Al4V alloy manufactured by high layer thickness laser-based directed energy position additive manufacturing process. No cracks were visibly present under the naked eye. Solidification cracking within a disposition boundary was present on some parts of the as-printed Ti6Al4V surface. Trans-deposition boundary cracks were visible under the optical microscope as liquation cracking. After polishing, the cracks were almost eliminated, with small isolated cracks on the polished surface. These cracks and concentrated C depositions confirmed with SEM-EDX can act as stress concentration points and crack initiation sites. SEM images showed α-lath structures with Widmanstätten pattern, and α+β Ti grains were observed. Post-processing methods such as removing the topmost crack surfaces, shot peening, laser shock peening and heat treatment can be adopted to reduce the cracks and enhance the performance of the as-deposited parts.

Keywords: additive manufacturing, cracking in additive manufacturing, laser-directed energy deposition, high layer thickness metal additive manufacturing, Ti6Al4V.

1. Introduction

Metal additive manufacturing (AM) is a rapidly progressing field with applications in aerospace [1], automobile [2], biomedical [3], and marine applications [4]. Laser-directed energy deposition (LDED) is a directed energy deposition (DED) AM process where laser power is used to fuse metals as it is being deposited according to design data [5–8]. Similar to the arc-DED process [9-13], the L-DED process has the capability of manufacturing parts with a higher deposition rate (i.e., layer thickness) than other metal AM processes like the powder bed fusion (PBF) processes such as selective laser melting (SLM), electron beam melting (EBM), etc. The layer thickness in PBF techniques generally ranges in microns, while in the DED process, it can be more than 1 mm [14,15]. The increased layer thickness enables a shorter manufacturing time, thus saving time and cost for production. This also comes with increased difficulties in terms of operation, complications in material properties, higher sensitivities to dimensional inaccuracies, and performance-related issues [15–18]. Favorable microstructural conditions are a prerequisite for an acceptable additively manufactured product. Finer microstructure provides higher strength, while coarser microstructures have more ductility [19]. Increasing the layer thickness results in a more diversified and increased grain size [20,21]. Determining such microstructures on additively manufactured products brings forth much-needed data and helps adjust the process and post-processing methods based on the requirements. Cracking during and after the metal AM process is also one of the main concerns leading to distortion and compromised performance of the fabricated parts [22].

Ti6Al4V is known to have high strength-to-weight ratio, biocompatibility, thermal stability, and good corrosion resistance [23]. Despite applications in aerospace [24–27], biomedical [28–30], and marine [31–33], manufacturing of Ti6Al4V alloy has been difficult due to its tendency of strain hardening, reactive to oxygen, and poor thermal conductivity [24,34–36]. The conventional manufacturing of Ti6Al4V follows a large amount of material wastage, a series of machining processes, and post-processing methods, often significantly increasing the manufacturing cost. Due to this, metal 3D printing of Ti6Al4V is becoming a popular alternative to conventional manufacturing processes. LDED process also allows the fabrication of complex shapes and highly customized products [23,37]. While most of the reported research is focused on the thin layer thickness AM processes, the research on the microstructure and surface cracking pattern on the high layer thickness LDED AM is still limited.

Formation of α laths and refinement of prior-β grains led to an increased tensile strength of 1091 MPa by 280 MPA and plasticity to 4.09% on Ti6Al4V alloy manufactured by the DED process

[38]. Lack of fusion defects is one of the common stress concentration points that act as crack initiation points. These defects can be on the surface as well as inside the additively manufactured parts. The main cause of lack of fusion defects is due to un-optimized process parameters [39]. Post-processing techniques like the HIP can significantly reduce these defects [40,41]. Solidification and liquation cracking have been the prominent types of cracking in additively manufactured parts. The long cracks in the fusion zone are due to the transmission of residual stress in the solidified dendrites. The liquation crack generally appears in the heat-affected zone due to repeated heating and cooling cycles [42]. Wang et al. reduced the cracks by tuning the process parameters to reduce the interaction between the crack-inducing phases during the additive manufacturing of Ti-48Al-2Cr-2Nb alloy [43]. Other methods to reduce crack formation include the addition of additional materials [44], HIP [40], surface removal during post-processing, shot peening [45–47], and laser shock peening [48–50]. Additively manufactured metal parts with minimum defects should be the target, even though the post-processing methods can mitigate these defects. Such research on high-layer thickness Ti6Al4V metal additive manufacturing is still limited. The present research is focused on the analysis of surface micro-cracks and microstructures of Ti6Al4V alloy fabricated by high-layer thickness laser-based DED additive manufacturing process.

2. Experimental methods and materials

The bulk block sample of 40 mm long, 60 mm width, and 150 mm height was prepared using MELTIO M450. The M450 is a wire feed-based laser-directed energy deposition machine. A laser power of 1000 W with a scanning speed of 10 mm/s and a layer thickness of 1mm was used to prepare the sample. An alternate 45° laser scanning pattern was employed during the Ti6Al4V alloy deposition. The average diameter of Ti6Al4V alloy was 1 mm diameter. Inert Argon gas with a flow rate of 20 L/min was supplied for an inert environment so that oxidation is minimized as much as possible. Initial 5 mm deposition was provided for easy removal of the additively manufactured part from the substrate and to pre-heat the substrate. The laser source, wire feed, and substrate are shown in Figure 1(a). The wire feed is located in the middle of the laser head and is surrounded by six lasers. The fabricated sample is shown in Figure 1(b).

The additively manufactured Ti6Al4V sample was removed from the substrate using wire-cut electric discharge machining (wire-EDM). The bulk sample was then divided into small sections for different tests. Before any post-processing, the printed raw surface was analyzed in an optical microscope to check the surface cracks and behavior. Then, the samples were polished with grit sizes ranging from 100 to 2200 and were etched using Kroll's reagent (92 ml water, 6 ml Nitric Acid, 2 ml Hydrofluoric Acid). These samples were placed under the same optical microscope and field emission scanning electron microscope-energy dispersive X-ray (FESEM-EDX) to investigate the micro-structure, cracks, and voids both on the surface and cross-sectionally. X-ray diffractometer (XRD) analysis was performed with a range of 25°- 90° to identify the constituent phase of the fabricated samples.

3. Results and discussions

The Ti6Al4V additively manufactured sample using the LDED process is shown in Figure 2 from different directions. Figure 2(a) shows the side view, 2(b) shows the front view, (c) shows the top view, and (d) shows the magnified view of the marked section of 2(b). As seen in Figure 2, overall proper deposition was observed, and the alternate 45° deposition pattern is also clearly observed at the top of the LDED prepared sample in Figure 2(c). Some spatters were also observed, as shown in Figure 2(b&d). These spatters are the result of an end or start of layer deposition. Even though larger spatters are not desirable, small spatters are bound to happen as the laser is turned off just after the tool path is finished for the layer. Turning off at the exact end of the tool path may result in improper and insufficient deposition of the Ti6Al4V alloy from the supplied wire spool. Spatters can be reduced if the toolpath is continuous while changing the layers, but excessive heating may occur, resulting in a higher tendency to distortion and the presence of higher residual stresses. For this, a gap of one minute was provided between each layer. A 5 mm raft at the bottom of the part was added to make the extraction of samples easy and to act as pre-heating the substrate to prevent excessive residual stress and distortion (Figure 2.a&b). The spatters and other physical defects should be removed during the post-processing.

There were no spatters, and smooth surface depositions were observed in the areas that were not the end or start of layer deposition, as seen in Figure 3(a&c). The presence of α and β Ti was confirmed with the XRD peaks. It revealed mainly α-Ti (JCPDS #44-1294) and some β-Ti (JCPDS #44-1288) phases in the Ti6Al4V alloy distribution, as shown in Figure 3(b) [51–54]. The manufactured surface was smooth, and there were no cracks under the naked eye. Macroscopically, the additively manufactured sample is absent of any unwanted cracks and lack of fusion due to the LDED process conditions. The patterns of deposition and changing of tracks as well as layers, are clearly seen in Figure 3(a&c).

Further examination of the as-printed Ti6Al4V surface using optical microscope shows the nature and distribution of the material on the surface. Figure 4 and Figure 5 show a microscopic image of the as-printed Ti6Al4V alloy. As mentioned above, no cracks were visible under the naked eye. Figure 4 shows an as-printed surface without cracks, while Figure 5 shows an as-printed surface with cracks. The different color curves show the boundary of fusion between different deposition tracks. Figure 4(a) shows a tri-junction of three different deposition or fusion boundaries. The yellow and orange curve shows the deposition fusion of the same layer, while the green curve shows the fusion from the next layer in a part of the re-melted yellow and orange deposition. Figure 4(b) shows another fusion boundary between two different layers. Figure 5 shows an as-printed Ti6Al4V surface with cracks on it. The cracks are inside the red mark in Figure 5(a), while the curve is the crack in Figure 5(b). Two types of cracks were observed: (a) cracks within a deposition track and (b) cracks that spread to other layers and deposition tracks. These solidification cracks developed during the solidification of the molten Ti6Al4V alloy. These cracks are due to the solidification shrinkage and thermal contraction during cooling that happens multiple times during the LDED additive manufacturing process [55]. When the solidification starts, the dendrite formation in the semi-solid region reduces the proper liquid flow, and due to the extreme heating and cooling cycle during the LDED process, tensile stresses develop and transmit in these regions, resulting in crack formation [56,57]. The trans-boundary cracks are developed due to continued solidification and the temperature differences between the current fusion zone and heat-affected zone (HAZ) as liquation cracking phenomenon.

These micro-cracks can act as stress concentration points and crack initiation points, leading to the failure of the additively manufactured parts. Further investigation were carried out to see if these surface micro-cracks were also present deep inside the fabricated part. It revealed that such cracks were primarily limited to the surface only. The constant re-melting of the previous layer eliminated the cracks that developed during the deposition in the last layer. Figure 6(a) shows the microscopic image of the polished Ti6Al4V surface without any cracks, while Figure 6(b) shows the cracks on other parts of the surface. These cracks were on the top surfaces after polishing. However, the cracks were negligible and were limited to small areas. The cracks spread like a river pattern with small tributaries from the main branch, sometimes connecting with other main branches. As mentioned above, these cracks will act as crack propagation points during loading, leading to failure of the parts. SEM images in Figure 7(a) show such cracks. The cracks had no clear patterns, but some were interconnected, like those in Figure 6(b). The dark dots in Figure 6(b) are concentrated carbon distribution as confirmed by SEM-EDX, as shown in Figure 7(b&c). A point EDX test on the dark spot revealed a spike in the Carbon content (67.41%) in the elemental distribution. During a high-layer thickness additive manufacturing process, such as in the laser-based directed energy deposition process, partial re-melting of previous layers and substrate pre-heating is vital to reduce crack formation. The pre-heating can be in the form of normal pre-heating or by providing a raft, as presented in the present paper, to act as pre-heating as well as provide sufficient space for the separation of the additively manufactured part and substrate as the fabrication is completed. Other post-processing methods, such as removing the top cracked surface, shot peening [58], laser shock peening [14], and other stress-relieving operations [59] can be applied to reduce the cracks imparted on the additively manufactured parts and improve the performance of the LDED manufactured parts.

SEM images showed α-lath structures with Widmanstätten pattern, as shown in Figure 8(a&b). In most parts, the cracks were absent. As the cooling starts above the transformation temperature, β grain starts growing, and once the temperature reaches below the transformation temperature, the α grain starts forming in the β grain boundaries. As the cooling continues, the α grain continues to grow across the β grains, forming α+β Ti grains. The high-temperature gradient during the heating and cooling cycle resulted in the formation of columnar grains as seen in Figure 8.

4. Conclusions

The high layer thickness additive manufacturing can significantly increase the material deposition rate, thus reducing completion time. This paper presents the surface cracking behavior and microstructure of Ti6Al4V alloy manufactured by multi-laser directed energy deposition additive manufacturing. Solidification cracking, which is known in welding and additive manufacturing process, were present on the as-printed Ti6Al4V surface. Some cracks were limited within a deposition track as solidification crackings, while some spread beyond a single deposition track to HAZ as liquation cracking. These cracks were significantly reduced once the surface was polished in the post-processing period. The limited cracks after polishing were in a river-like pattern, with tributaries connecting with other cracks. There were some concentrated Carbon distributions confirmed by SEM-EDX. These cracks and concentrated C depositions can act as stress concentration points and crack initiation sites during loading. SEM images showed α-lath structures with Widmanstätten pattern along with α+β Ti grains with columnar grains. Post-processing, pre-heating, and partial re-melting of previous layers are some measures to reduce crack formation. Post-processing methods include removing the topmost crack surfaces, polishing, shot peening, laser shock peening, and other stress-relieving operations to reduce the crack and enhance the performance of the additively manufactured parts.

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Data availability statement

Data will be made available upon reasonable request.

Conflict of interest

The authors declare that they have no known competing financial interest or personal relationships that could have appeared to influence the work reported in this paper.

References

1. Careri, F., Khan, R. H. U., Todd, C., et al. “Additive Manufacturing of Heat Exchangers in Aerospace Applications: A Review”, *Applied Thermal Engineering*, p. 121387 (2023). DOI: 10.1016/J.APPLTHERMALENG.2023.121387.
2. Zhao N., Parthasarathy, M., Patil, et al. “Direct additive manufacturing of metal parts for automotive applications”, *Journal of Manufacturing Systems*, **68**, pp. 368–375 (2023). DOI:10.1016/j.jmsy.2023.04.008.
3. Zhang, Q. and Guan, Y., “Application of metal additive manufacturing in oral dentistry”, *Current Opinion in Biomedical Engineering*, **25**, p. 100441 (2023). DOI: 10.1016/j.cobme.2022.100441.
4. Chandrasekaran, S., Hari, S., and Amirthalingam, M., “Functionally graded materials for marine risers by additive manufacturing for high-temperature applications: Experimental investigations”, *Structures*, **35**, pp. 931–938 (2022). DOI: 10.1016/j.istruc.2021.12.004.
5. Svetlizky, D., Zheng, B., Vyatskikh, A., et al. “Laser-based directed energy deposition (DED-LB) of advanced materials”, *Materials Science and Engineering: A*, **840**, p. 142967 (2022). DOI: 10.1016/j.msea.2022.142967.
6. Liu, F. Q., Wei, L., Shi, S. Q., et al. “On the varieties of build features during multi-layer laser directed energy deposition”, *Additive Manufacturing*, **36**, p. 101491 (2020). DOI: 10.1016/j.addma.2020.101491.
7. Tudu, N., Baruah, M., and Prasad, S. B., “Comparison of properties at the interface of deposited IN625 and mixture of IN625 SS304L by laser directed energy deposition and SS304L substrate”, *Rapid Prototyping Journal*, **29**(4), pp. 818–827 (2023). DOI: 10.1108/RPJ-08-2021-0219.
8. Li, Z., Sui, S., Ma, X., et al. “High deposition rate powder- and wire-based laser directed energy deposition of metallic materials: A review”, *International Journal of Machine Tools and Manufacture*, **181**, p. 103942 (2022). DOI: 10.1016/j.ijmachtools.2022.103942.
9. Cam, G. and Gunen, A., “Challenges and opportunities in the production of magnesium parts by directed energy deposition processes”, *Journal of Magnesium and Alloys*, **12**(5), p. 1663-1686 (2024). DOI: 10.1016/j.jma.2024.05.004.
10. Cam G., “Prospects of producing aluminum parts by wire arc additive manufacturing (WAAM)”, *Materials Today: Proceedings*, **62**(1), p. 77-85 (2022). DOI: 10.1016/j.matpr.2022.02.137.
11. Bolukbasi, O.S., Serindag, T., Gurol, U., et al. “Improving oxidation resistance of wire arc additive manufactured Inconel 625 Ni-based superalloy by pack aluminizing”, CIRP *Journal of Manufacturing Science and Technology*, **46**, p. 89-97 (2023). DOI: 10.1016/j.cirpj.2023.07.011.

12. Gurol, U., Altinay, Y., Gunen, A., et al. "Effect of powder-pack aluminizing on microstructure and oxidation resistance of wire arc additively manufactured stainless steels", *Surface & Coating Technology*, **468**, p. 129742 (2023). DOI: 10.1016/j.surfcoat.2023.129742.

13. Gunen, A., Gurol, U., Kocak, M., et al. "Investigation into the influence of boronizing on the wear behavior of additively manufactured Inconel 625 alloy at elevated temperature", *Progress in Additive Manufacturing*, **8**, p. 1281-1301 (2023). DOI: 10.1007/s40964-023-00398-8.

14. Singh, S. N. and Deoghare, A. B., "Laser Shock Peening of Laser Based Directed Energy Deposition and Powder Bed Fusion Additively Manufactured Parts: A Review", *Metals and Materials International*, **29**(6), pp. 1563–1585 (2023). DOI: 10.1007/s12540-022-01334-1.

15. Singh, S. N. and Deoghare, A. B., "Macrodimensional accuracy of Ti6Al4V parts manufactured by wire-feed high layer thickness continuous laser directed energy deposition", *Journal of Laser Applications*, **35**(1), p. 012003 (2023). DOI: 10.2351/7.0000870.

16. Yang, Y., Gong, Y., Li, C., et al. "Mechanical performance of 316 L stainless steel by hybrid directed energy deposition and thermal milling process", *Journal of Materials Processing Technology*, **291**, p. 117023 (2021). DOI: 10.1016/j.jmatprotec.2020.117023.

17. Cao, L., Li, J., Hu, J., et al. "Optimization of surface roughness and dimensional accuracy in LPBF additive manufacturing", *Optics and Laser Technology*, **142**, p. 107246 (2021). DOI: 10.1016/j.optlastec.2021.107246.

18. Ertay, D. S., Vlasea, M., and Erkorkmaz, K., "Thermomechanical and geometry model for directed energy deposition with 2D/3D toolpaths", *Additive Manufacturing*, **35**, p. 101294 (2020). DOI: 10.1016/j.addma.2020.101294.

19. Arora, H. S., Ayyagari, A., Saini, J., et al. "High Tensile Ductility and Strength in Dual-phase Bimodal Steel through Stationary Friction Stir Processing", *Scientific Reports*, **9**(1), pp. 1–6 (2019). DOI: 10.1038/s41598-019-38707-3.

20. Santana, A., Eres-Castellanos, A., Jimenez, J. A., et al. "Effect of layer thickness and laser emission mode on the microstructure of an additive manufactured maraging steel", *Journal of Materials Research and Technology*, **25**, pp. 6898–6912 (2023). DOI: 10.1016/j.jmrt.2023.07.114.

21. Liu, M., Wei, K., and Zeng, X., "High power laser powder bed fusion of AlSi10Mg alloy: Effect of layer thickness on defect, microstructure and mechanical property", *Materials Science and Engineering: A*, **842**, p. 143107 (2022). DOI: 10.1016/j.msea.2022.143107.

22. Brennan, M. C., Keist, J. S., and Palmer, T. A., "Defects in Metal Additive Manufacturing Processes", *Journal of Materials Engineering and Performance*, **30**(7), pp. 4808–4818 (2021). DOI: 10.1007/s11665-021-05919-6.

23. Liu, S. and Shin, Y. C., "Additive manufacturing of Ti6Al4V alloy: A review", *Materials and Design*, **164**, p. 107552 (2019). DOI: 10.1016/j.matdes.2018.107552.

24. Parry, L., Ashcroft, I. A., and Wildman, R. D., "Understanding the effect of laser scan strategy on residual stress in selective laser melting through thermo-mechanical simulation", *Additive Manufacturing*, **12**, pp. 1–15 (2016). DOI: 10.1016/j.addma.2016.05.014.

25. Uhlmann, E., Kersting, R., Klein, T. B., et al. "Additive Manufacturing of Titanium Alloy for Aircraft Components", *Procedia CIRP*, Elsevier, pp. 55–60 (2015). DOI: 10.1016/j.procir.2015.08.061.

26. Singh, P., Pungotra, H., and Kalsi, N. S., "On the characteristics of titanium alloys for the aircraft applications", *Materials Today: Proceedings*, Elsevier, pp. 8971–8982 (2017). DOI: 10.1016/j.matpr.2017.07.249.

27. Boyer, R. R., "An overview on the use of titanium in the aerospace industry", *Materials Science and Engineering: A*, **213**(1–2), pp. 103–114 (1996). DOI: 10.1016/0921-5093(96)10233-1.

28. Hao, Y. L., Li, S. J., and Yang, R., "Biomedical titanium alloys and their additive manufacturing", *Rare Metals*, **35**(9), pp. 661–671 (2016). DOI: 10.1007/s12598-016-0793-5.

29. Ciocca, L., Fantini, M., De Crescenzio, F., et al. "Direct metal laser sintering (DMLS) of a customized titanium mesh for prosthetically guided bone regeneration of atrophic maxillary arches", *Medical and Biological Engineering and Computing*, **49**(11), pp. 1347–1352 (2011). DOI: 10.1007/s11517-011-0813-4.

30. Emmelmann, C., Scheinemann, P., Munsch, M., et al. "Laser additive manufacturing of modified implant surfaces with osseointegrative characteristics", *Physics Procedia*, Elsevier, pp. 375–384 (2011). DOI: 10.1016/j.phpro.2011.03.048.

31. Cui, C., Hu, B. M., Zhao, L., et al. "Titanium alloy production technology, market prospects and industry development", *Materials and Design*, **32**(3), pp. 1684–1691 (2011). DOI: 10.1016/j.matdes.2010.09.011.

32. Gurrappa, I., "Characterization of titanium alloy Ti-6Al-4V for chemical, marine and industrial applications", *Materials Characterization*, **51**(2–3), pp. 131–139 (2003). DOI: 10.1016/j.matchar.2003.10.006.

33. Gorynin, I. V., "Titanium alloys for marine application", *Materials Science and Engineering: A*, **263**(2), pp. 112–116 (1999). DOI: 10.1016/s0921-5093(98)01180-0.

34. Prasad, A. V. S. R., Ramji, Koona., and Datta, G. L., "An Experimental Study of Wire EDM on Ti-6Al-4V Alloy", *Procedia Materials Science*, **5**, pp. 2567–2576 (2014). DOI: 10.1016/j.mspro.2014.07.517.

35. de Formanoir, C., Brulard, A., Vivès, S., et al. "A strategy to improve the work-hardening behavior of Ti–6Al–4V parts produced by additive manufacturing", *Materials Research Letters*, **5**(3), pp. 201–208 (2017). DOI: 10.1080/21663831.2016.1245681.

36. Gupta, R. K., Kumar, V. A., Mathew, C., et al. "Strain hardening of Titanium alloy Ti6Al4V sheets with prior heat treatment and cold working", *Materials Science and Engineering: A*, **662**, pp. 537–550 (2016). DOI: 10.1016/j.msea.2016.03.094.

37. Huang, R., Riddle, M., Graziano, D., et al. "Energy and emissions saving potential of additive manufacturing: the case of lightweight aircraft components", *Journal of Cleaner Production*, **135**, pp. 1559–1570 (2016). DOI: 10.1016/j.jclepro.2015.04.109.

38. Zhang, H., Zhang, L., Chen, H., et al. “Complete fine-equiaxed β-columnar grains in laser direct energy deposition of Ti-6Al-4V parts”, *Journal of Materials Research and Technology* (2023). DOI: 10.1016/J.JMRT.2023.08.208.

39. Tammas-Williams, S., Zhao, H., Léonard, F., et al. “XCT analysis of the influence of melt strategies on defect population in Ti-6Al-4V components manufactured by Selective Electron Beam Melting”, *Materials Characterization*, **102**, pp. 47–61 (2015). DOI: 10.1016/j.matchar.2015.02.008.

40. Kok, Y., Tan, X. P., Wang, P., et al. “Anisotropy and heterogeneity of microstructure and mechanical properties in metal additive manufacturing: A critical review”, *Materials and Design*, **139**, pp. 565–586 (2018). DOI: 10.1016/j.matdes.2017.11.021.

41. Lewandowski, J. J. and Seifi, M., “Metal Additive Manufacturing: A Review of Mechanical Properties”, *Annual Review of Materials Research*, **46**, pp. 151–186 (2016). DOI: 10.1146/annurev-matsci-070115-032024.

42. Guo, C., Li, G., Li, S., et al. “Additive manufacturing of Ni-based superalloys: Residual stress, mechanisms of crack formation and strategies for crack inhibition”, *Nano Materials Science*, **5**(1), pp. 53–77 (2023). DOI: 10.1016/j.nanoms.2022.08.001.

43. Wang, M., Du, Y., Wei, H., et al. “From crack-prone to crack-free: Eliminating cracks in additively manufactured Ti-48Al-2Cr-2Nb alloy by adjusting phase composition”, *Materials and Design*, **231**, p. 112025 (2023). DOI: 10.1016/j.matdes.2023.112025.

44. Han, Q., Gu, Y., Setchi, R., et al. “Additive manufacturing of high-strength crack-free Ni-based Hastelloy X superalloy”, *Additive Manufacturing*, **30**, p. 100919 (2019). DOI: 10.1016/j.addma.2019.100919.

45. Gundgire, T., Jokiaho, T., Santa-aho, S., et al. “Comparative study of additively manufactured and reference 316 L stainless steel samples – Effect of severe shot peening on microstructure and residual stresses”, *Materials Characterization*, **191**, p. 112162 (2022). DOI: 10.1016/j.matchar.2022.112162.

46. Soyama, H. and Kuji, C., “Improving effects of cavitation peening, using a pulsed laser or a cavitating jet, and shot peening on the fatigue properties of additively manufactured titanium alloy Ti6Al4V”, *Surface and Coatings Technology*, **451**, p. 129047 (2022). DOI: 10.1016/j.surfcoat.2022.129047.

47. Maleki, E., Bagherifard, S., Heydari Astaraee, A., et al. “Application of gradient severe shot peening as a novel mechanical surface treatment on fatigue behavior of additively manufactured AlSi10Mg”, *Materials Science and Engineering: A*, **881**, p. 145397 (2023). DOI: 10.1016/j.msea.2023.145397.

48. Sandmann, P., Keller, S., Kashaev, N., et al. “Influence of laser shock peening on the residual stresses in additively manufactured 316L by Laser Powder Bed Fusion: A combined experimental–numerical study”, *Additive Manufacturing*, **60**, p. 103204 (2022). DOI: 10.1016/j.addma.2022.103204.

49. Bai, Y., Lyu, G. J., Wang, Y. J., et al. “Laser shock peening strengthens additively manufactured high-entropy alloy through novel surface grain rotation”, *Materials Science and Engineering: A*, **871**, p. 144886 (2023). DOI: 10.1016/j.msea.2023.144886.

50. Hamidi Nasab, M., Vedani, M., Logé, R. E., et al. “An investigation on the fatigue behavior of additively manufactured laser shock peened AlSi7Mg alloy surfaces”, *Materials Characterization*, **200**, p. 112907 (2023). DOI: 10.1016/j.matchar.2023.112907.

51. Da Silva, S. L. R., Kerber, L. O., Amaral, L., et al. “X-ray diffraction measurements of plasma-nitrided Ti-6Al-4V”, *Surface and Coatings Technology*, **116–119**, pp. 342–346 (1999). DOI: 10.1016/S0257-8972(99)00204-2.

52. Fiołek, A., Zimowski, S., Kopia, A., et al. “The influence of electrophoretic deposition parameters and heat treatment on the microstructure and tribological properties of nanocomposite Si3N4/PEEK 708 coatings on titanium alloy”, *Coatings*, **9**(9), p. 530 (2019). DOI: 10.3390/coatings9090530.

53. Wysocki, B., Maj, P., Sitek, R., et al. “Laser and electron beam additive manufacturing methods of fabricating titanium bone implants”, *Applied Sciences*, **7**(7), p. 657 (2017). DOI: 10.3390/app7070657.

54. Dinda, G. P., Song, L., and Mazumder, J., “Fabrication of Ti-6Al-4V scaffolds by direct metal deposition”, *Metallurgical and Materials Transactions A: Physical Metallurgy and Materials Science*, **39**(12), pp. 2914–2922 (2008). DOI: 10.1007/s11661-008-9634-y.

55. Platl, J., Bodner, S., Hofer, C., et al.“Cracking mechanism in a laser powder bed fused cold-work tool steel: The role of residual stresses, microstructure and local elemental concentrations”, *Acta Materialia*, **225**, p. 117570 (2022). DOI: 10.1016/j.actamat.2021.117570.

56. Rappaz, M., Drezet, J. M., and Gremaud, M., “A new hot-tearing criterion”, *Metallurgical and Materials Transactions A: Physical Metallurgy and Materials Science*, **30**(2), pp. 449–455 (1999). DOI: 10.1007/S11661-999-0334-Z/METRICS.

57. Sun, Z., Tan, X. P., Descoins, M., et al. “Revealing hot tearing mechanism for an additively manufactured high-entropy alloy via selective laser melting”, *Scripta Materialia*, **168**, pp. 129–133 (2019). DOI: 10.1016/j.scriptamat.2019.04.036.

58. Aguado-Montero, S., Navarro, C., Vázquez, J., et al. “Fatigue behaviour of PBF additive manufactured TI6AL4V alloy after shot and laser peening”, *International Journal of Fatigue*, **154**, p. 106536 (2022). DOI: 10.1016/j.ijfatigue.2021.106536.

59. Teixeira, Ó., Silva, F. J. G., Ferreira, L. P., et al. “A review of heat treatments on improving the quality and residual stresses of the Ti–6Al–4V parts produced by additive manufacturing”, *Metals*, **10**(8), pp. 1–24 (2020). DOI: 10.3390/met10081006.

Fig. 1: (a) printing chamber of M450 and (b) printed bulk sample.

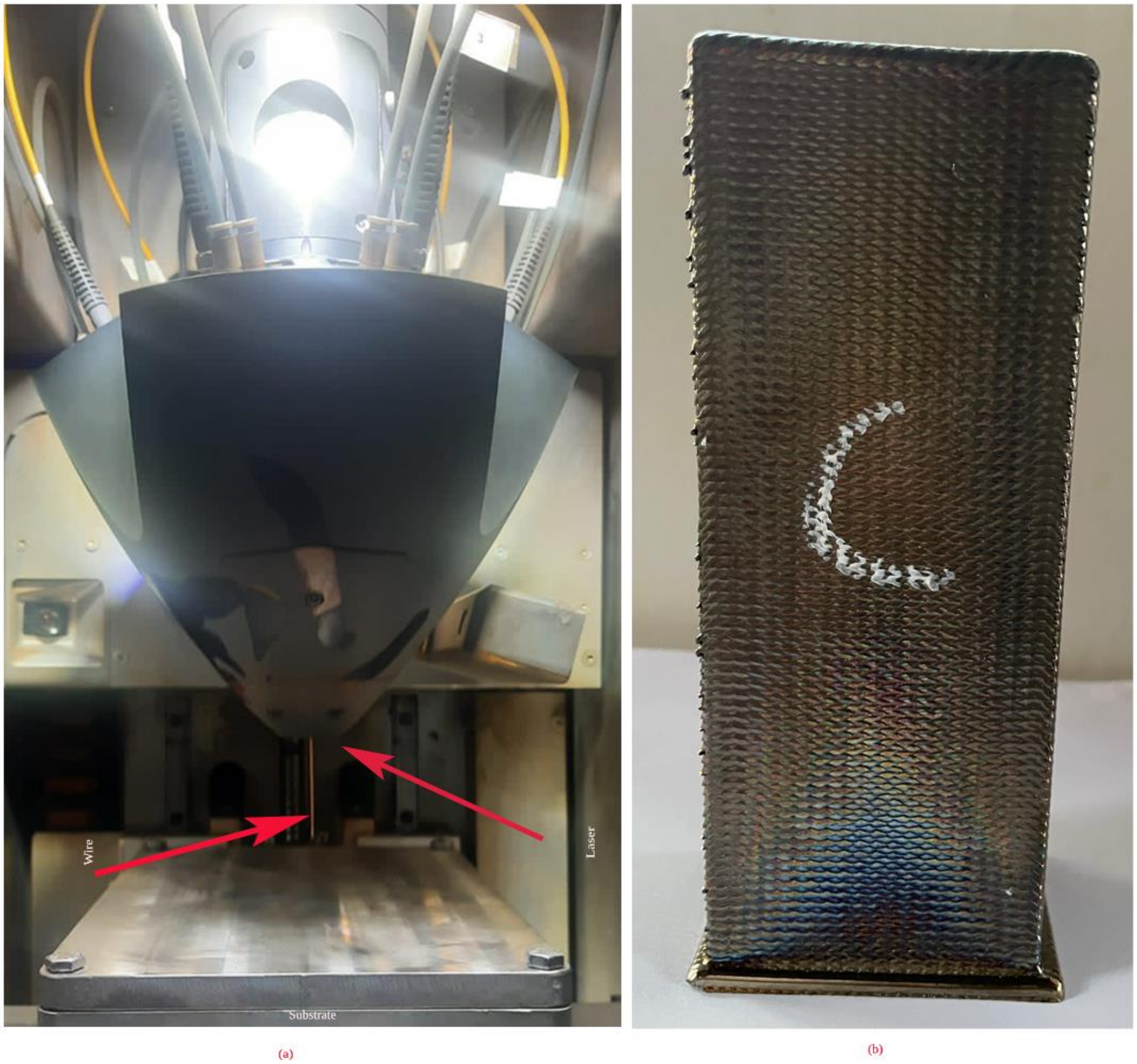


Fig. 2: (a) side view, (b) front view, (c) top view of the fabricated parts, and (d) presence of spatters on the additively manufactured part.

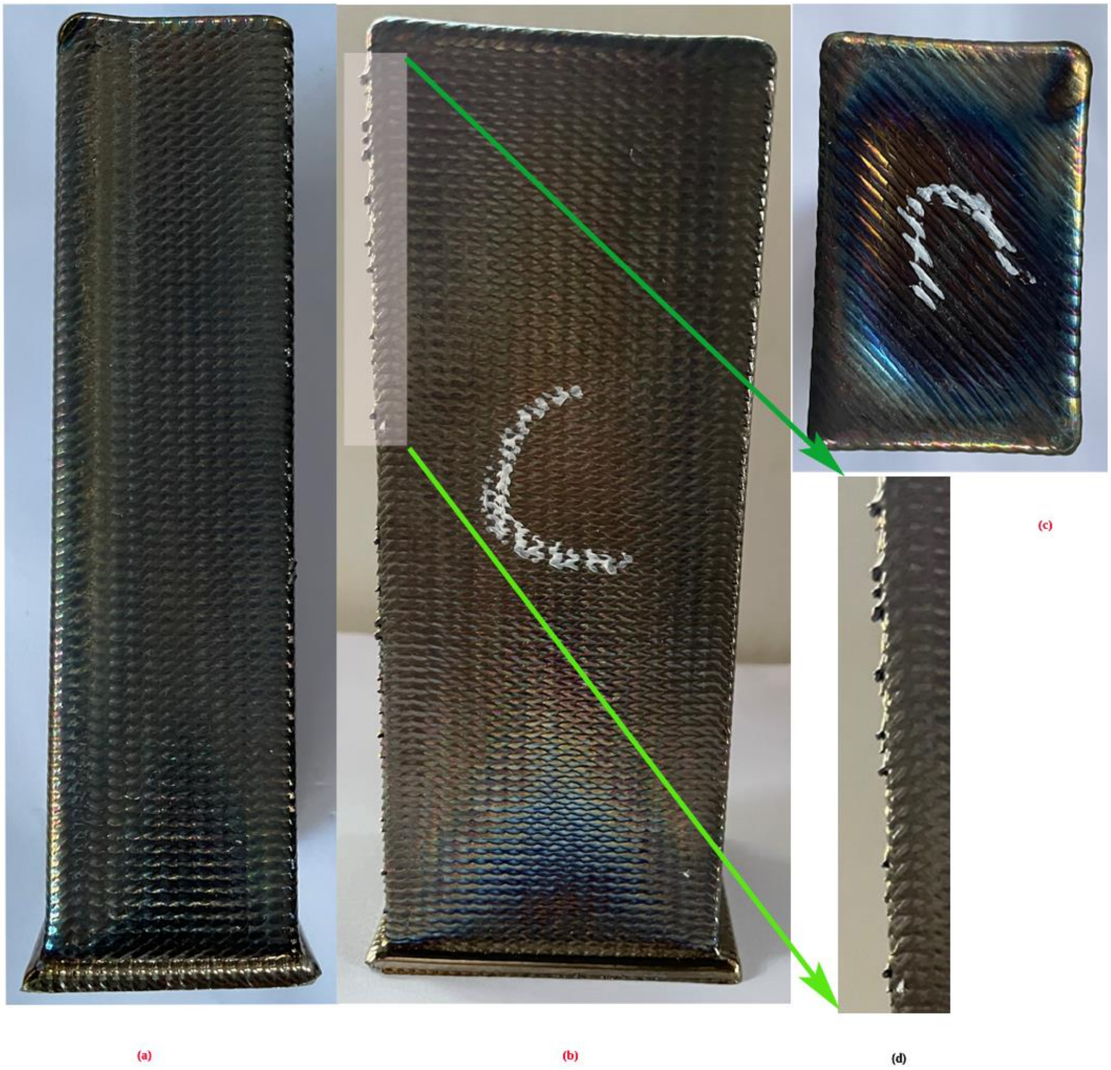
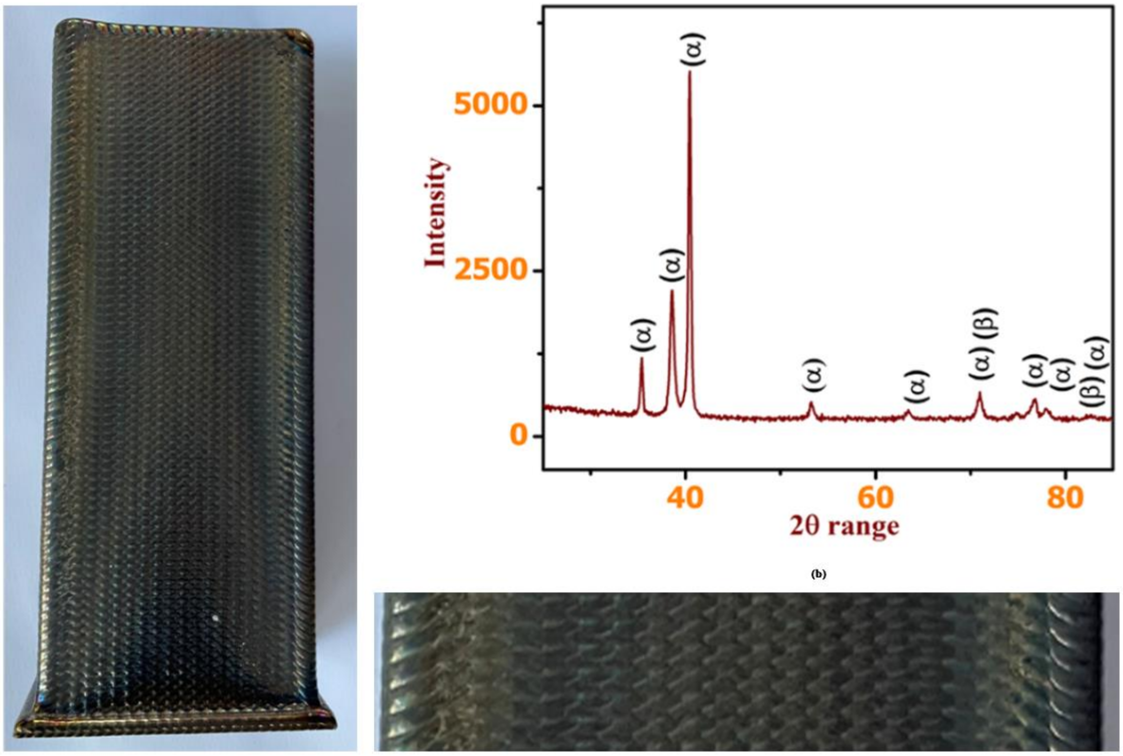


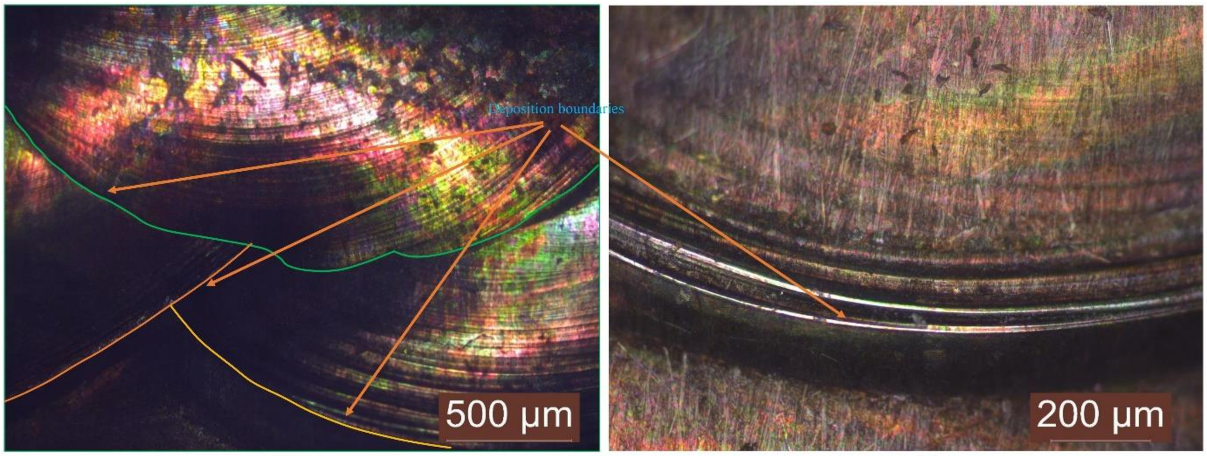
Fig. 3: (a) Ti6Al4V spatter-free surface manufactured by LDED process, (b) XRD pattern of the additively manufactured Ti6Al4V alloy, and (c) a magnified portion of (a).



(a)

(c)

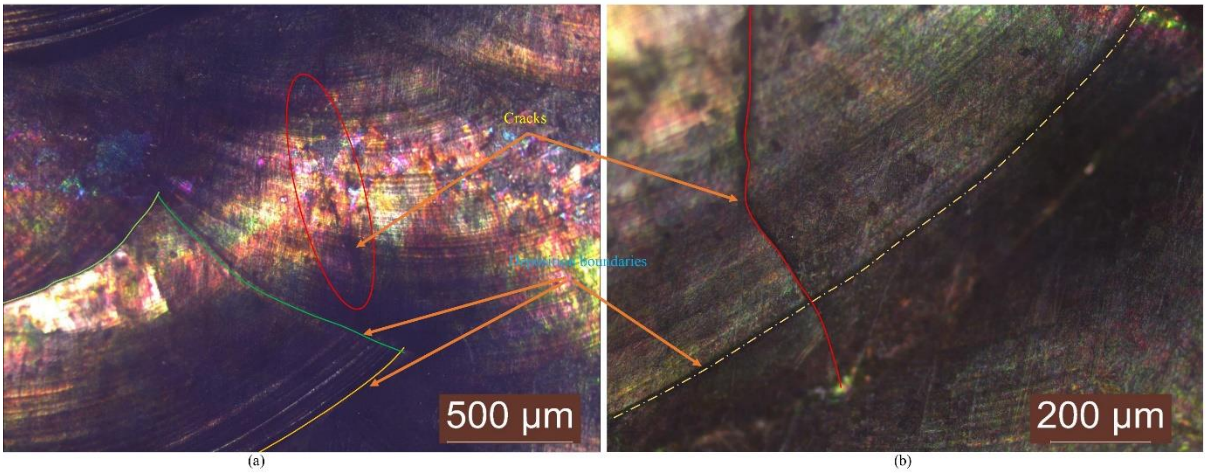
Fig. 4: (a) and (b) Fusion boundaries between different layers and scan tracks on as-printed Ti6Al4V alloy fabricated by LDED process.



(a)

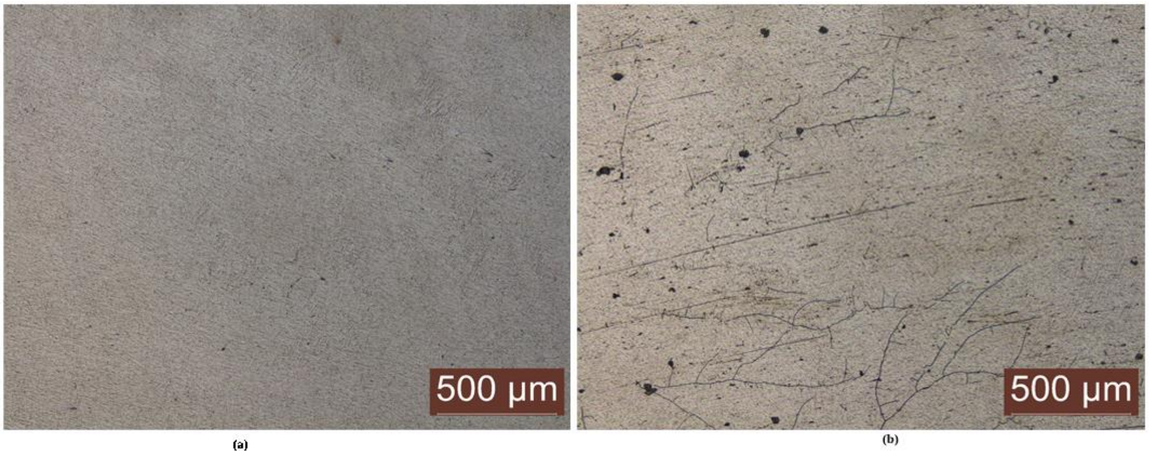
(b)

Fig. 5: (a) cracks within a deposition zone, and (b) trans-deposition boundary cracks in additively manufactured Ti6Al4V surface.



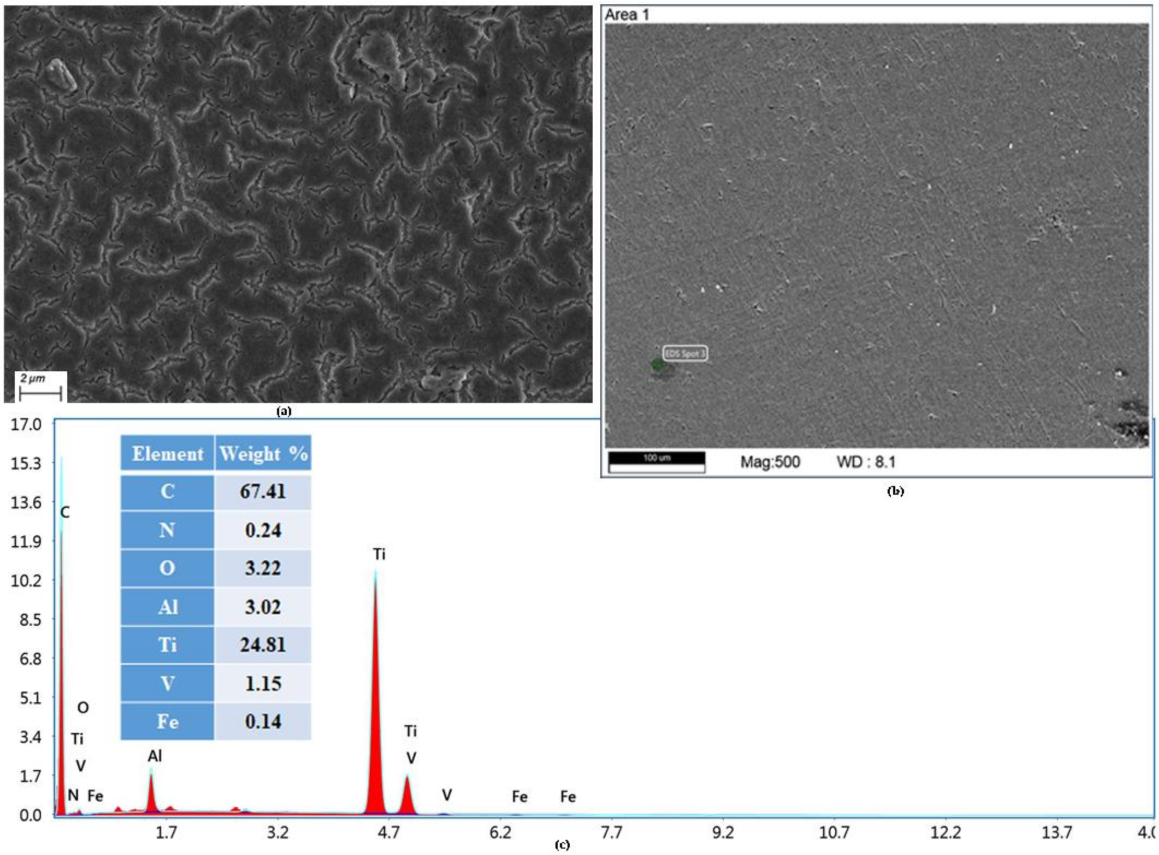
(a) (b)

Fig. 6: (a) microscopic image of additively manufactured Ti6Al4V surface after polishing, and (b) cracks on the polished surface.



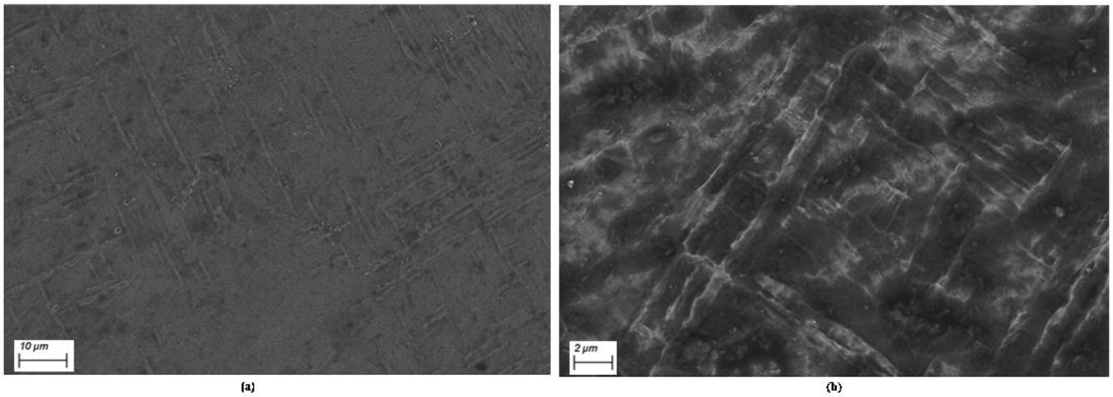
(a) (b)

Fig. 7: SEM images of (a) crack surfaces, (b&c) concentrated Carbon dots.



Element	Weight %
C	67.41
N	0.24
O	3.22
Al	3.02
Ti	24.81
V	1.15
Fe	0.14

Fig. 8: (a), (b) microstructure of additively manufactured Ti6Al4V under SEM.



Biographies

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