Generative Design and Topology Optimization of Analysis and Repair Work of Industrial Robot Arm Manufactured Using Additive Manufacturing Technology

M. Kumaran 1*, V. Senthilkumar 1
1 Department of Production Engineering, National Institute of Technology Tiruchirappalli, Tamil Nadu, India – 620015

E-mail: kumumech@gmail.com

Abstract. Today’s industrial robots work in a wide range of industries, the industrial robots are developed to perform operations such as pick and place, manufacturing assembly line, welding work, metal forging, and painting operations. The constraints of available robots are in terms of structural complexity, more material in the body, over weightage, and space. To overcome the difficulties of the current scenario, the generative design and topology optimization based industrial robot arm is manufactured by Additive Manufacturing (AM) technology using the Powder Bed Fusion (PBF) process. The scope of the research is when the generatively designed robot arm getting crack or broken, the Direct Energy Deposition (DED) processes use to help the repair of the PBF parts. In the present research, studies were conducted on the topology optimized industrial robot arm using SolidWorks software, and to verify the significance of DED to extend requirements needed for PBF parts, sample parts were extended and their metallurgical characteristics, tensile properties, and hardness observed.

Keywords: Additive Manufacturing, Generative Design, Topology Optimization, Robot Arm, Industrial Robot

1. Introduction
An industrial robot [1] structure is the main drawback, it has an over material quantity and more body weight of the robot. Modern industrial robot production with AM technology [2, 3] is used to resolve the major drawback. The technology of AM directly produces the component using laser-powder technology with the help of a generative design and topology optimization method. Generating design and topology optimization of additive components can address unwanted materials and overcome the 30% - 70% weight reduction range. The scope of the research is to analyze the case study of when getting the external crack or broken part in additive manufactured robot arm to resolve using repair work by the DED process.

Unless it is topologically optimized, the weight of each part in the assembly may exceed the required weight. The extra weight means too much material is used, the load on the moving parts exceeds the necessary level, energy efficiency is compromised, and the cost of transporting parts is higher. Now, using topology optimization techniques, it is necessary to lightweight components,
design durable for any application. To ensure that manufacturing specifications are met, set minimum material thicknesses, and identify exclusion areas, you may easily define targets and apply controls.

2. **Design Methodology**

1. **Generative design and topology optimization**

Through generative design and topology optimization [4], these simulation techniques allow the use of simulation-driven design methods to customize lightweight designs and high-performance parts. Advances in manufacturing technology have also allowed the use of processes such as metal additive manufacturing to build these sometimes complex designs [5].

![Figure 1. Topology optimization designed robot arm and stress analysis.](image)

As shown in **Figure 1**, the topology optimization design used by SolidWorks software help to reduce the material consumption at 50% from the original design and robot arm weight is minimized from 1.55kg to 0.77kg. The latest SolidWorks software utilizes the topology optimization function to eliminate the design weight once, thereby reducing material consumption by 50%. In the design analysis, Stainless Steel 316L (SS 316L) material was used. Von-Mises stress is the value used to determine whether a given material yields or breaks. After topology optimization, the design part is analyzed under the action of external force, and the maximum Von-Mises stress is 68.25 MPa. Use the finite element model of the robot arm for stress analysis, which can control both stress and strain loading conditions. The stress distribution is affected by the material and physical properties.

2. **Simulation of metal-based additive manufacturing processes**

**Figure 2.** shows the manufacture based simulation process in AM using altair inspire print3D software [6]. It is used to optimize the process parameters of the manufacturing conditions. While varying primary process parameters such as laser power (W) 190, 200 and 210 respectively; scanning speed (mm/s) 800, 900 and 1000 respectively; layer thickness (μm) 200, 300 and 400 respectively.
Based on the results of the minimum residual stress (50 Mpa), the laser power is 195 W, the scanning speed is 900 mm/s and the layer thickness is 400 μm.

3. Experimental Results

1. Making the component using additive manufacturing (PBF Process)

In this research, spherical granules of SS 316L [7] in the range of 5 - 45 μm diameter were used for PBF process, with the chemical composition as follows Fe 68.34; Cr 16.62; Ni 10.57; Mo 2.11; Si 0.60; Mn 1.58; C 0.030; N 0.10; P 0.035; S 0.020. As shown in Figure 3(a), the morphology of SS 316L powder was observed by a Field Emission Scanning Electron Microscope (FE-SEM), which specified approximately spherical shaped powder particles. Figure 3(b), are the histograms with an average particle size of 22 μm diameter by intensity size distribution. The study results shown in Figure 3(c), An Energy-Dispersive X-ray spectrometer (EDAX) (Elemental analysis) measured the powder for element ratios, indicating that the chemical composition meets the standard value of SS 316L.
Figure 3. SS 316L powder: (a) FE-SEM morphology for PBF; (b) Histogram of particle size distribution; and (c) EDAX results of SS 316L powder for PBF.

It was used to make a robot arm of PBF with a scanning speed 900 mm/s, laser power of 195 W, hatching pitch of 100 μm, layer thickness of 400 μm and laser diameter of 0.2 mm. These values are the same as those used for the simulation of metal-based additive manufacturing processes using the altair inspire print3D software based on the least residual stress and the best mechanical properties. Specimens were manufactured in a highly clean argon gas chamber. Figure 4(a) in this study, tensile samples were prepared vertically using the ASTM (E8) standard [8]. Figure 4(b) shows the tensile test result for manufactured PBF specimen [9]. Figure 4(c) magnifies the PBF of the fractured Sample. Dimples are observed in this area. Figure 4(d) shows the result of the stress-strain value of the tensile specimen sample of the yield stress of the PBF sample is 564 MPa, at a total elongation of 45.5%. When the ultimate force used was 7440 N, it withstood the ultimate stress at 675 MPa.

(a) (b)
2. Repairing the component using additive manufacturing (DED Process)

Repairing work experiments [10, 11] were conducted to establish the best condition for extension while varying primary process parameters such as powder feed rate (PR) 2, 3 and 4 g/min respectively; scanning speed (SS) 300, 500 and 700 mm/min respectively; and laser power (P) 400, 600 and 800 W respectively. The objective was to evaluate the deposition characteristics according to the requirements of the L9 Taguchi-method. Cross-section of the DED product under different process conditions. Based on the harness analysis (225.4 HV) and microstructural results, processing conditions of powder feed rate of 4 g/min, 500 mm/min scanning speed and 600 W laser power were selected as optimal conditions. Spherical granules of SS 316L in the range of 50 - 150 μm diameter were used for the DED process, the histograms with an average particle size of 80 μm diameter. **Figure 5(a)** To extend the DED additive manufacturing process, the PBF substrate used various parameters. The PBF substrate prepared were of 15 mm height (Z-axis, upright position), and using the DED process extended the remaining 15 mm height above the substrate. Finally, DED extended above the PBF surface area. The PBF specimen was extended up to a height of 15 mm using the DED process as shown in **Figure 5(b)** and **Figure 5(c)**. Portions A and B are a cross-section of PBF specimen extended by DED, based on the extended height. It shows the Sandwich Structure (SWS).
portion C [12]. The extended DED showed no cracking, and revealed excellent metallurgical bonding between the substrate and the extended region.

![Figure 5](image1.png)

**Figure 5**(a) DED extended specimen (SWS) (b) and (c) Microstructural images of extended SWS specimens.

**Figure 6**(a) shows the tensile test result for manufactured the extended process (SWS) specimen. **Figure 6**(b) magnifies the extended area of the fractured specimen. Dimples are observed in this area. **Figure 6**(c) The results of the extended process (SWS) tensile test specimens, the sandwich structure specimen's yield stress was 380 MPa, at a total elongation of 23.4%. When the ultimate force used was 6170 N, it withstood the ultimate stress at 536 MPa.
Figure 6 (a) Macro image of PBF specimens, after tensile testing (b) Micro-fractography of fractured specimen, and (c) Engineering stress-strain curve of SWS SS 316L.

4. Conclusion
This paper has studied the generative design and topology optimization of robot arm fabricated by metal additive manufacturing using SS 316L powder. To evaluate the design, mechanical properties and microstructures were analyzed. The robot arm optimized with low residual stress also fabricated with 50% of weight reduction using metal additive manufacturing. Finally, we conclude in this paper that the metal additive manufacturing is suitable for robot arm also sandwich structure specimen of SS 316L is suitable for extended or repairing applications.

References
[1] Francesco De Pace, Federico Manuri, Andrea Sanna and Claudio Fornaro 2020 A systematic review of Augmented Reality interfaces for collaborative industrial robots Computers & Industrial Engineering 149 106806
[2] Amit Bandyopadhyay and Kellen D Traxel 2018 Invited review article: Metal-additive manufacturing-Modeling strategies for application-optimized designs Additive Manufacturing 22 758-774
[3] V. Senthilkumar, C. Velmurugan, KR. Balasubramanian and M. Kumaran 2020 Additive Manufacturing of Multi-Material and Composite Parts Additive Manufacturing Applications for Metals and Composites, IGI Global 127-146
[4] Mustafa Bugday and Mehmet Karali 2019 Design optimization of industrial robot arm to minimize redundant weight Engineering Science and Technology an International Journal 22 346-352
[5] Fei Weng, Shiming Gao, Jingchao Jiang, JianJian Wang and Ping Guo 2019 A novel strategy to fabricate thin 316L stainless steel rods by continuous directed energy deposition in Z direction Additive Manufacturing 27 474-481
[6] Noha Peter, Zachary Pitts, Spencer Thompson and Ankit Saharan 2020 Benchmarking build simulation software for laser powder bed fusion of metals Additive Manufacturing 20 30903-9
[7] Yong-Deok Im, Kyung-Hoon Kim, Kyung-Hwan Jung, Young-Kook Lee and Kuk-Hyun Song 2019 Anisotropic Mechanical Behavior of Additive Manufactured AISI 316L Steel Metallurgical and Materials Transactions A 50 2014-2021
[8] Zhaopeng Tong, Xudong Ren, Jiafei Jiao, Wangfan Zhou, Yunpeng Ren, Yunxia Ye, Enoch Asuako Larson and Jiayang Gu 2019 Laser additive manufacturing of FeCrCoMnNi high-entropy alloy: Effect of heat treatment on microstructure, residual stress and mechanical property Journal of Alloys and Compounds 785 1144-1159
[9] Zan Li, Thomas Voisin, Joseph T. McKeown, Jianchao Ye, Tom Braun, Chandrika Kamath, Wayne E. King and Y. Morris Wang 2019 Tensile properties, strain rate sensitivity, and activation volume of additively manufactured 316L stainless steels International Journal of Plasticity 120 395-410
[10] Wook Jin Oh, Wook Jin Lee, Min Seob Kim, Jong Bae Jeon and Do Sik Shim 2019 Repairing additive-manufactured 316L stainless steel using direct energy deposition Optics & Laser Technology 117 6-17
[11] G.F. Sun, X.T. Shen, Z.D. Wang, M.J. Zhan, S. Yao, R. Zhou and Z.H. Ni 2019 Laser metal deposition as repair technology for 316L stainless steel: Influence of feeding powder compositions on microstructure and mechanical properties Optics & Laser Technology 109 71-83
[12] Xinchang Zhang, Wei Li, Xueyang Chen, Wenyuan Cui and Frank Liou 2018 Evaluation of component repair using direct metal deposition from scanned data The International Journal of Advanced Manufacturing Technology 95 3335-3348

Acknowledgment
Thanks are largely due to Mr. A.R. Vinod, Scientist-C and Mr. B.N. Manjunath, Scientist-B at the Additive Manufacturing Technology Division, Central Manufacturing Technology Institute, Bangalore, India, for conducting the characterization and experiments of the PBF and DED processes. Also, I gratefully acknowledge the support of staff members at PSG Tech’s COE INDUTECH Laboratory, Coimbatore, India, for conducting the FESEM and EDAX studies.