Parameters Optimization Model and Solution Method Based on 3D Manufacturable Units

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Abstract—At present, the lightweight design methods for SLM (Selective Laser Melting) process cannot meet the performance requirements while maintaining the consistency of the appearance of parts, and there are some defects in material cost and processing efficiency. In order to improve these defects, this paper proposed a lightweight reconstruction parameters optimization model based on 3D manufacturable units, and finite element simulation and Matlab calculation were used to solve the model to obtain the optimal structural parameters. Finally, the reconstruction design of typical parts was taken as an example to verify the feasibility of the model and the solution method.

1. Introduction

Metal 3D printing technology provides a more accurate and efficient means for the maintenance and support of weapons and equipments in the battlefield environment. Through the reasonable design of parts structure, this technology can not only meet the strength requirements of actual working conditions, but also reduce the redundant materials inside parts under the constraints of traditional processes. By using this technology, the lightweight of parts is achieved, which not only reduces the waste of materials, but also improves the efficiency of maintenance support⁴¹.² At present, there are four main methods to achieve the lightweight of metal parts with SLM technology at the structural optimization level: lattice sandwich structure², hollow lattice structure⁴, integrated structure⁵ and topological optimization structure⁷. The structure examples are shown in Fig.1.
Although these four lightweight methods can achieve weight reduction to a certain extent, they cannot simultaneously meet the double requirements of consistent shape and sufficient strength of parts. In order to solve this problem, Zhang Z.X's team of National University of Defense Technology proposed a method of lightweight reconstruction of parts by using "3D manufacturable units". 3D manufacturable units (hereinafter referred to as manufacturable units), refer to the internal filling units of parts that can be formed smoothly by SLM process without reducing the mechanical properties of the parts and at the same time achieve the lightweight effect of parts. By adjusting the structural parameters of the units, the optimal lightweight effect can be achieved on the premise of satisfying the strength performance, and through the reasonable skin design, this method can also maintain the consistency of the shape of the parts. At present, this method has achieved some research results. The previous research mainly used compression test to establish the parameters-performance database of the manufacturable units under different design parameters which was used as the basis for determining the optimal parameters of the manufacturable units. Using this method, the test cost is high and the cycle is long, which is not conducive to the rapid lightweight reconstruction of parts. To solve this problem, this paper proposed a parameters optimization model of parts' lightweight reconstruction based on the manufacturable units, and determined the optimal parameters by solving the model, so as to achieve the fast lightweight reconstruction of parts on the premise of meeting the strength requirements.

2. The establishment and solution of parameters optimization model

2.1. The manufacturable units geometry models

Manufacturable units are divided into bearing units and auxiliary support units according to their functions. At present, the manufacturable units and their geometry models developed by the team are shown in Tab.1. The bearing units are the basis of the design of parts reconstruction. Yan C [7] of National University of Defense Technology obtained several typical skeleton carrying units (01,02,03) by using topological optimization and normalization method. According to the characteristics of plate spring, Zhang Q.B et al. [8] studied an impact-resistant elastic damping structural unit (04). In addition to bearing capacity, it can also improve the impact-resistant performance through effective energy
absorption. Yun Z et al. [9] of Central South University designed the bending and pressure resistance units (05) by imitating the structure of the bridge. The auxiliary support units are support structure for the overhang structure inside the parts, which effectively overcome the constraints of 3D printing manufacturing, and avoid the deterioration of forming quality or forming failure. TANG L et al. [10,11] studied a tree-like support structure (07), and HE L.J et al. [12] designed a honeycomb support structure with variable density (06). After certain parameter design, the honeycomb structure can also be used as a bearing unit. Through simulation analysis and experimental verification, the above two support structures can be formed smoothly and play a good supporting role.

| Classification         | Name                      | No. | Geometric model |
|------------------------|---------------------------|-----|----------------|
| Bearing units          | Torsional skeleton        | 01  | ![Image](image1) |
|                        | Flange torsion skeleton   | 02  | ![Image](image2) |
|                        | Rectangular & Ring compresive skeleton | 03 | ![Image](image3) |
|                        | Elastic damping element   | 04  | ![Image](image4) |
|                        | Bending stress learning unit | 05 | ![Image](image5) |
| Auxiliary support units| Honeycomb structure unit  | 06  | ![Image](image6) |
|                        | Treelike support structure | 07 | ![Image](image7) |

2.2. The establishment of parameters optimization model
According to the actual load condition of the parts, the corresponding units are selected to fill the internal structure. In order to achieve the effect of lightweight and high strength, it is necessary to set the structural parameters of the unit reasonably. Based on finite element simulation, this paper established a parameters optimization model of the manufacturable units, and used the model to solve
the problem to obtain the optimal structural parameters that meet the requirements of lightweight and high strength design.

2.2.1. Design variables and evaluation indicators

First, the design parameter $X$ of the manufacturable units was introduced: $X = (x_1, x_2, ..., x_n)^T$. $X$ is an $N$-dimensional vector, and the dimensions are equal to the number of design parameters. Then, according to the design requirements of lightweight and high strength parts, two kinds of evaluation indicators were introduced, namely, lightweight ratio $p(X)$ and safety factor $K(X)$, and were defined as follows:

$$p(X) = 1 - \frac{\rho_c \times V_c(X)}{\rho_0 \times V_0}$$

(1)

$V_0$ and $V_c(X)$ represent the volumes of the part before and after reconstruction (the unit parameter is $X$, and the hollow part is not included in the volume). $\rho_0$ and $\rho_c$ represent the densities of the material before and after reconstruction. By default, the same material before and after reconstruction is used in this paper, namely $\rho_0 = \rho_c$. Then the lightweight ratio can be simplified as follows:

$$p(X) = 1 - \frac{V_c(X)}{V_0}$$

(2)

In terms of safety factor, the ultimate stress that the parts can bear should be greater than the allowable bearing force (ultimate stress $>\text{allowable stress}$), that is:

$$K(X) = \frac{\sigma_s}{\sigma_m(X)} > 1$$

(3)

$\sigma_s$ represents the ultimate yield strength of the material used for metal parts SLM forming. $\sigma_m(X)$ represents the maximum equivalent stress value obtained by finite element simulation of reconstructed parts under specific boundary conditions when the design parameter of the manufacturable unit is $X$.

2.2.2. The optimization model

In the process of lightweight reconstruction, it is required to achieve the lightest quality on the premise of satisfying safe performance. If the safety factor of the part is known to be $K_0$ under specific working conditions, then there should be $K(X) \geq K_0$. However, this condition is not required to be optimal and can be converted into a constraint condition when the parameter optimization model is established. According to the above analysis, the parameters optimization model of manufacturable units is obtained:

- **Design variable**: $X$
- **Design constants**: $\sigma_s$, $G$, $\mu$, $K_0$
- **Target function**: $\max p(X) \equiv \min V_c(X)$
- **Constraint**: $K(X) \geq K_0 \Leftrightarrow \sigma_m(X) \leq \frac{\sigma_s}{K_0} \Leftrightarrow h(p) \leq 0$

In the model, $G$ represents the elastic modulus of the material, and $\mu$ represents Poisson's ratio, belonging to the category of design constants, which are used for the material parameter setting of finite element simulation. $h(p)$ is determined by the value range of the design variable, which need to be analyzed and determined by integrating various factors such as the configuration of manufacturable units and SLM process manufacturing constraints.

2.2.3. The solution method of the model

When using this model to obtain the optimal structural parameter $X$, m parameter points can be selected and the corresponding $V_c(X_i)(i=1,2,3,...,m)$, $\sigma_m(X_i)(i=1,2,3,...,m)$ can be calculated through finite element analysis. Taking $X$ as independent variable, the function expressions of $V_c$ and $\sigma_m$ on variable $X$ can be fitted, and then the optimal solution can be obtained.

Since most of the structural parameters of manufacturable units are continuous variables, they can be solved by conventional linear or nonlinear optimization algorithms. For the optimization problem
of discrete variables, special optimization algorithms are needed, such as the branching and bounded method to solve similar mixed integer nonlinear programming problem (MINLP) \cite{13}. Through the above analysis, the solution process of parameters optimization model of manufacturable units can be obtained as follows:

a) According to the material properties and working conditions of the parts, the values of design constants $\sigma_s$, $G$, $\mu$ and $K_0$ are determined;
b) According to the design parameter $X$ of the manufacturable units, parametric modeling is carried out for the reconstructed parts by using Solidworks;
c) According to SLM process manufacturing constraints and design constraints, the value range of design variables is determined;
d) $V_c$ and $\sigma_m$ values under different $X$ values are obtained through ANSYS sampling simulation. Matlab is used to fit the function expressions of $V_c$ and $\sigma_m$ about $X$, and the objective function and constraint conditions are obtained. According to the design variable type, nonlinear optimization algorithm or mixed integer nonlinear optimization algorithm is selected to solve the model.

3. The application case

Next, combined with the actual part, the process of model establishment and solution is illustrated. Fig. 2 shows the flange rotary structure of a transmission component. The outer flange bolt holes are fixed, and the inner surface of the flange is applied with the torque of "500N-m". It is required that the safety factor of reconstruction can reach 4 after it is filled with manufacturable units, that is, $K_0=4$. 316L stainless steel powder is used for 3D printing of the reconstructed part, and the parameters are shown in Tab. 2.

![Fig.2 Flange rotary parts structure drawing](image)

| Material     | Density (kg/m$^3$) | Poisson's ratio | Modulus of elasticity (GPa) | Yield strength (MPa) |
|--------------|--------------------|----------------|-----------------------------|----------------------|
| 316L stainless steel | 7.9                | 0.3            | 200                         | 240                  |

Topological optimization and regular design method \cite{7} is used to obtain the flange torsion skeleton suitable for flange torsion configuration parts through SolidWorks modeling, as shown in Fig. 3(a). For flanged rotary parts with dimensions and configurations determined, the only design parameter of the filled flange torsion skeleton is the width $b$ of the reinforcement plate, as shown in Fig. 3(b).

![Fig.3(a) Flange torsion skeleton](image)
In order to ensure the reliability of the structure and the normal printing of thin-wall structure, the minimum structure size should not be less than 1mm \[^7\]. In order to save the time of simulation analysis, the upper limit of \( b \) value is temporarily set as 5. If no qualified value is found within this range, the upper limit of \( b \) value can be appropriately increased until an appropriate \( b \) value is found. The design variable range of flange torsion skeleton parameter optimization model is set as:

\[
1 \leq b \leq 5
\]  \( (5) \)

In order to find out the variation rules of \( V_c \) and \( \sigma_m \) about \( b \), Direct Optimization module in Ansys Workbench can be used for sampling simulation analysis. The specific steps are as follows: First, Solidworks is used for parametric modeling and the skeleton width design variable is set as DS_\( b \) (Parameter names cannot be identified by Ansys Workbench without the DS prefix); the parametric model is imported into Ansys Workbench for structural mechanics simulation and parameter optimization analysis \[^{14}\], and the maximum equivalent stress value \( \sigma_m \) and the volume \( V_c \) of the reconstructed part are set as output variables. Set various parameters according to corresponding projects in Ansys Workbench. Set design variable \( b \) as continuous variable and set the value range according to Formula (5). Set the sample quantity as 21. Through simulation analysis, the corresponding values of \( V_c \) and \( \sigma_m \) under 21 groups of different parameters can be obtained. Then, the function relations of \( V_c \) and \( \sigma_m \) on \( b \) can be obtained by Matlab, as shown in Formula (6) and (7), and the graphs are shown in Fig.4.

\[
V_c = -100.7b^2 + 3067b + 10370
\]  \( (6) \)

\[
\sigma_m = -2.269b^3 + 26.91b^2 - 113.1b + 227.1
\]  \( (7) \)

(a) The relationship graph of \( V_c \) with respect to \( b \)
According to Formula (5), (6) and (7), the parameter optimization model is transformed into the nonlinear optimization standard form:

$$\begin{aligned}
\min \quad & V_c \\
\text{s.t.} \quad & \sigma_m \leq 60 \\
& b \leq 5 \\
& b \geq 1
\end{aligned}$$

The design variable $b$ represents the thickness and it is a continuous variable. The fmincon function of Matlab optimization toolbox can be directly used to solve the optimization model, and the optimal solution is $b=4.1$mm (1 decimal point is reserved).

Under the same boundary conditions, the structural mechanics simulation analysis was carried out on the reconstructed parts when $b=4.1$mm, and the equivalent stress nephogram was obtained, as shown in Fig.5. The maximum equivalent stress value is 59.789mpa, the volume is 21248.38mm$^3$, and the lightweight ratio reaches 58.5%, meeting the requirements of lightweight reconstruction.

4. Conclusions

Aiming at the lightweight process design of metal 3D printing on part structure, this paper proposed a lightweight reconstruction parameters optimization model based on manufacturable units. The optimal structure parameters can be obtained by using finite element simulation and fitting operation to complete the rapid reconstruction of parts. Through the reconstruction of typical flange parts, the feasibility of the model and its solution method were verified. And this model will provide a more efficient means for the lightweight reconstruction of metal parts.

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