Optimal Design of Barrel Based on Selective Laser Melting

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Abstract. Selective Laser Melting (SLM) is an additive manufacturing technology based on melting layers of metal powder using powerful laser without traditional limits. SLM makes it possible to manufacture complex structures such as enclosed inner cavity and complex surface. However, most of the mechanical parts are designed according to the requirements of traditional processing technology. There is often material redundancy in these parts, which will seriously affect the speed of SLM printing and increase the cost of SLM printing. In this article, according to the actual working condition, the barrel of a grenade cartridge based on traditional process design was optimized using a method of interior lattice structure to achieve the goal of lightweight, to eliminate material redundancy as much as possible. Then the strength and printability of the optimized parts were verified.

Keywords: laser melting, Material redundancy, Selective laser melting

1. Introduction
Grenade cartridge is a kind of light weapon which can shoot small grenades. There are two meanings to optimize the design of the barrel of the grenade cartridge. One is to reduce the time cost of SLM printing, speeding up the forming speed, and the other is to reduce the weight of the cartridge and the mass of the carrier. Therefore, on the premise of ensuring the strength and safety of the barrel, the weight of the barrel should be reduced as much as possible.

The optimization work for barrel is developing rapidly. At present, the optimization design of barrel mainly focuses on three aspects: mass, strength and rigidity. Xu et al [1] constructed the composite optimization algorithm and the finite element model of barrel, and achieved the structural optimization design of composite material barrel wall thickness and winding angle under the constraint of mass, structural rigidity and structural strength. In order to achieve the multi-objective optimization of the quality, rigidity and stress of the barrel, the optimization design of the barrel charging parameters and the structure size was completed by using the algorithm of neural network and genetic algorithm [2]. However, these optimization methods are only for the traditional machining process design. We can use the flexibility of 3D printing technology (SLM) to optimize the barrel.

2. Structure Analysis of original design
When the grenade is ejected, the bottom and the wall of the barrel bear huge impact force. If the strength of the barrel (Fig.1) is not enough, the wall and the bottom of the barrel could be yield or broken. The
high-speed and high-temperature gas eject may cause casualties. The failure of the grenade ejection will cause huge potential safety hazard, which will seriously threaten the safety of the operators.

Figure 1. Original design of barrel

2.1. Working condition analysis
In the barrel, the maximum pressure in the bore is not generated at the muzzle. The maximum bore pressure can be estimated according to the average bore pressure in the bore [3], which can be known from the interior ballistic equation [4]:

$$SP = \varphi m \frac{dv}{dt}$$ (1)

where $S$ is the cross-sectional area of the barrel, $P$ is the average pressure in the bore, and $\varphi$ is the coefficient of secondary work calculation, which can be set as 1.00 for this type of grenade launcher. $m$ is the mass of the projectile, $V$ is the instantaneous velocity of the projectile in the bore, and $t$ is the time of the projectile in the bore. By integrating both sides of equation (1) at the same time, we can get:

$$\bar{P} \approx \frac{\varphi m V_0}{St_s}$$ (2)

In equation (2), $\bar{P}$ is the average pressure in bore, $V_0$ is the initial velocity of grenade ejection, and the relationship between the maximum pressure and the average pressure as follow:

$$\bar{P} \approx \frac{P_m}{2.1} \Rightarrow P_m = 2.1 \bar{P}$$ (3)

The time of grenade in barrel $t_s$:

$$t_s \approx \frac{2l_s}{V_0}$$ (4)

It can be derived from equation (1) ~ (4) that:

$$P_m \approx \frac{1.05 \varphi m V_0}{St_s}$$ (5)

According to the relevant parameter of this type of projectile and the actual use of the projectile, it can be estimated that the maximum chamber pressure is 15MPa:

$$P_m \approx 15MPa$$ (6)

2.2. Static structural mechanics simulation analysis
In the process of grenade ejection, the whole inner wall of the barrel does not bear the maximum chamber pressure, and the pressure changes with time and grenade displacement [5]. So set the maximum bore pressure(15MPa) as the boundary condition (Fig.2), use ANSYS Workbench to carry out static mechanical analysis on the barrel, and obtain the stress distribution could be obtain as shown in Fig. 3.
3. Optimal design

According to the optimization method proposed in paper [6]. The optimization design process of the barrel can be carried out in accordance with splitting parts, selecting lattice structure splicing module, designing auxiliary detail, FEA verification and other steps. The optimization process is as shows in Fig.4:

3.1. Splitting parts

The barrel is a typical main swivel part. According to the stress distribution of the indicated barrel under the maximum bore pressure, the barrel model can be segmented into three modules based on the step...
surface segmentation basis [6], as shown in Fig.5. Ignoring the thread characteristics of module III, all of them belong to the typical rotary body.

Module I am mainly used to coordinate with the lower baffle to locate the bottom of the barrel. When the grenade is ejected, the stress is not large and the requirements for strength and rigidity are not high. In addition, under the chamber pressure, the maximum equivalent stress value of the area where module I is located is 8Mpa, which is far lower than the yield strength of stainless steel.

Module II is the main stress part of the barrel under the chamber pressure, which has a high requirement for strength. According to the simulation analysis results, the maximum equivalent stress value in the area of module II is 19.78MPa, which is far less than the yield limit of the material, and there is material redundancy. For module II, the optimization design process can be carried out with lattice structure, and the safety factor s can be set to 4.

The maximum equivalent stress of the inner tube wall of module III under the action of bore pressure is as high as 125.19MPa. Because the maximum equivalent stress value will be greater after optimization, and high temperature, high pressure and high-speed air flow will act on the inner wall of bore, effecting ejection performance of barrel, so Module III cannot be optimized.

![Figure 5. Model segmentation diagram.](image)

Table 1 shows the processing method for each module.

| Module No. | Module Function  | Processing Method                                |
|------------|------------------|-------------------------------------------------|
| I          | Location         | Shell (1mm)                                     |
| II         | Pressure bearing | Shell(2mm) and Filling lattice structure         |
| III        | Pressure bearing | No optimization                                 |

3.2. Selecting lattice structure
According to the analysis above, the design space of module II can be filled with lattice structure. Because the module II is mainly under pressure, the ring compression skeleton or honeycomb structure can be selected as the internal filling structure [7]. The parameterized models of two kinds of modules filled with different lattice structure are built and imported into ANSYS Workbench. the safety factor (S) and Weight loss ratio ($k_w$) of module II filling with honeycomb structure and ring anti-pressure skeleton can be obtained under different parameters, as shows in Fig. 6.
With the required safety factor under the boundary conditions of the maximum bore pressure, the optimization effect of honeycomb structure element in module II is better than that of ring anti-pressure skeleton.

According to the solution, the design variable side length and wall thickness of the honeycomb structure which meets the safety factor and has the best lightweight effect are 3.5mm and 1mm respectively. The honeycomb structure with the above parameters is used to fill the module II after shell extraction, and the mass of the optimized module II is reduced by 62%.

3.3. Splicing module
In SolidWorks, the side length and wall thickness of the honeycomb structure are set to 3.5mm and 1mm respectively, and the 3D model after optimization of module II has been obtained. Then, the optimized module I, module II and module III without any change are spliced into parts with the same shape as shown in Fig.1, but the internal structure changes. Section after splicing is shown in Fig. 7.

3.4. Designing auxiliary detail
There are a large number of closed cavities in the optimized module I and module II. In order to eliminate the metal powder in the closed cavity, the powder hole with small stress in module I can be set as a circle with a diameter of 2mm. On the honeycomb wall far away from the bore pressure of the optimized module II, the powder hole is designed according to the optimized powder hole shape as described in paper [7], as shown in Fig.8. For the closed cavity formed by honeycomb structure, it can be regarded as the closed cavity of revolving body, and a fillet with a radius of 3.5mm is set in each closed cavity formed by honeycomb structure. Finally, through the quality evaluation of the whole part, the whole weight of the optimized barrel can be reduced by 31%.
3.5. Finite element analysis verification

In order to verify the part strength after optimization, set the same boundary conditions as shown in Fig.2 and mesh with the same parameters to obtain the stress cloud (Fig.9) and deformation cloud (Fig.9) of the part after barrel optimized. As shown in Fig.9, it can be seen that the equivalent stress value of the area where module II is located increases compared with that before optimization, but the maximum equivalent stress value is lower than 60MPa, which meets the requirements of the safety factor.

![Figure 9. Optimized design stress cloud](image)

4. SLM process simulation analysis

In order to verify the printability of the optimized design model, SLM process simulation analysis is carried out for the optimized barrel by using software named Simfactory Additive [8], and the simulation process is shown in Fig.10.

1. Import model. Import the part model and set the relative position of the part on the base plate, generally in the middle.

2. Add auxiliary support. It is mainly to add auxiliary supports to the suspended area. Since the system will automatically identify and add supports, the support structure will be generated by default in the suspended area of the optimized part. These supports should be removed manually.

3. Mesh. Setting the related parameters of grid division, the smaller the grid division unit is, the more accurate the simulation results are, but the amount of calculation is large and the simulation time is long. In order to ensure the simulation accuracy, the partition voxel size is set to 1mm;

4. Simulation solution. According to the sequence of 3D printing forming, heat treatment, substrate separation and support removal added in the process, four sub processes are simulated and solved step by step; the setting parameters of each sub process are completely set according to the parameters in the actual processing flow.

5. Post processing. After processing the simulation data, a more intuitive cloud chart is formed.

![Figure 10. SLM process simulation](image)

The z-direction displacement distribution of the optimized forerunner is similar. Because of the powder hole design in the second module of the optimized barrel, the area of the second module is shifted to the negative z-axis. The maximum Z-direction displacement of the optimized barrel is 0.07mm, which is 0.03mm larger than the maximum Z-direction displacement of the optimized barrel. However,
for the barrel, 0.04mm is within the acceptable range, and the optimized barrel can be formed smoothly. If the accuracy requirement for SLM parts is high, the compensation design can be carried out for the optimized barrel to eliminate the shrinkage deformation caused by thermal stress during SLM printing.

![Original barrel vs Optimized barrel](image)

**Figure 11.** Z-direction displacement cloud of AM layer for original and optimized barrel

5. Conclusions

(1) In the optimization design, lattice structure is used to fill the interior of the parts, which reduces the weight by 31% and the safety factor is up to 3.

(2) As the optimized structure is designed according to SLM process design criteria, the forming time is shortened by 31%. Because it is quite difficult to deal with after structure.

(3) The results of SLM process simulation show that for thick wall parts, the combination of lattice structure filling and 3D printing can produce a lighter and better performance structure.

Acknowledgments

The authors would like to thank for Tao Jiang for teaching the way to use the simulation software Simfactory Additive.

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