МІНІСТЕРСТВО ОСВІТИ ТА НАУКИ УКРАЇНИ

НАЦІОНАЛЬНИЙ АВІАЦІЙНИЙ УНІВЕРСИТЕТ

КАФЕДРА КОНСТРУКЦІЇ ЛІТАЛЬНИХ АПАРАТІВ

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Завідувач кафедри, д.т.н., проф.
___________ Сергій ІГНАТОВИЧ
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«АВІАЦІЙНА ТА РАКЕТНО-КОСМІЧНА ТЕХНІКА»

Тема: «Чисельне моделювання лазерної ударної обробки шестерень авіаційних двигунів»

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MINISTRY OF EDUCATION AND SCIENCE OF UKRAINE

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DEPARTMENT OF AIRCRAFT DESIGN

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«___» _______________ 2022

MASTER DEGREE THESIS

ON SPECIALITY

"AVIATION AND AEROSPACE TECHNOLOGIES "

Topic: "Numerical simulation of laser shock peening of aircraft engine gears"

Fulfilled by: ____________ **Longgang FAN**

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Kyiv 2022

НАЦІОНАЛЬНИЙ АВІАЦІЙНИЙ УНІВЕРСИТЕТ

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«_____» _____________ 2022 р.

ЗАВДАННЯ

на виконання кваліфікаційної роботи пошукача

ЛУНГАН ФАНЬ

1.□□ Тема роботи: «Чисельне моделювання лазерної ударної обробки шестерень авіаційних двигунів», затверджена наказом ректора від 05 жовтня 2022 року №1861/ст.

2.□□ Термін виконання роботи: з 06 жовтня 2022 р. по 30 листопад 2022 р.

3.□□ Вихідні дані до роботи: кінцеве-елементна модель зубчастого колеса.

4.□□ □□Зміст пояснювальної записки: аналіз ефективності застосування лазерної обробки, аналіз оптимальних параметрів лазерної обробки, моделювання процесу лазерної обробки методом скінченних елементів та оцінка впливу кожного параметра на ефект зміцнення, обґрунтування оптимальних параметрів лазерної обробки для зміцнення поверхні шестерень авіаційних двигунів.

5. Перелік обов'язкового графічного (ілюстративного) матеріалу: презентація Power Point, малюнки та схеми.

6. Календарний план-графік:

№	Завдання	Термін виконання	Відмітка про виконання
1	Огляд літератури про принципи технології лазерного зміцнення.	06.10.2022–13.10.2022	
2	Застосування технології лазерного зміцнення в авіації та аналіз матеріалів зубчастих передач	14.10.2022–24.10.2022	
3	Аналіз оптимальних параметрів процесу обробки методом скінченних елементів	25.10.2022–01.11.2022	
4	Визначення закономірностей впливу параметрів обробки на ефект зміцнення поверхневих шарів.	6.10.2022–23.10.2022	
5	Виконання частин, присвячених	24.10.2022–31.10.2022	

	захисту середовища і праці.		
6	Підготовка ілюстративного матеріалу, написання пояснювальної записки.	1.11.2022–7.11.2022	
7	Перевірка, редагування та виправлення пояснювальної записки.	7.11.2022–10.11.2022	

7. Консультанти з окремих розділів:

Розділ	Консультант	Дата, підпис	
		Завдання видав	Завдання прийняв
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8. Дата видачі завдання: 5 жовтня 2022 року

Керівник дипломної роботи ____________ Вадим ЗАКІЄВ

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NATIONAL AVIATION UNIVERSITY

Aerospace Faculty

Department of Aircraft Design

Educational Degree «Master»

Specialty 134 «Aviation and Aerospace Technologies»

Educational Professional Program «Aircraft Equipment»

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Head of Department,

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________ Serhiy IGNATOVYCH

«___» ________________ 2022

TASK

for the master degree thesis

Longgang FAN

1. Topic: «Numerical simulation of laser shock peening of aircraft engine gears», approved by the Rector's order № 1861 «05» October 2022.

2. Period of work: since 05 October 2022 till 10 November 2022.

3. Initial data: finite element model of a gear

4. Content: analysis of the laser processing effectiveness, analysis of optimal parameters of laser processing, simulation of the laser processing process using the finite element method and assessment of the influence of each parameter on the strengthening effect, substantiation of optimal parameters of laser processing for strengthening the surface of aircraft engine gears.

5. Required material: Power Point Presentation, drawings and diagrams.

6. Thesis schedule:

№	Task	Time limits	Done
1	Review of the literature on the principles of laser hardening technology.	06.10.2022–13.10.2022	
2	Application of laser hardening technology in aviation and analysis of gear materials.	14.10.2022–24.10.2022	
3	Analyze the optimal process parameters of single point impact hole wall and hole circumference.	25.10.2022–01.11.2022	
4	Analysis of optimal parameters of the laser shock peening process using the finite element method	06.10.2022–23.10.2022	
5	Execution of the parts, devoted to environmental and labor protection.	24.10.2022–31.10.2022	
6	Preparation of illustrative material, writing the report.	01.11.2022–07.11.2022	
7	Explanatory note checking, editing and correction.	07.11.2022–10.11.2022	

7. Special chapter advisers:

Chapter	Adviser	Date, signature	
		Task issued	Task received
Labor protection	PhD, associate professor Catarina KAZHAN		
Environmental protection	Dr. Sc., professor Lesya PAVLYUKH		

8. Date of issue of the task: 10 September 2022 year

Supervisor: ____________ Vadim ZAKIEV

Student: ____________ Лунган фань

РЕФЕРАТ

Пояснювальна записка кваліфікаційної роботи «Чисельне моделювання лазерної ударної обробки шестерень авіаційних двигунів»

75 с., 29 рис., 3 табл., 25 джерел

Об'єкт дослідження – Лазерна обробка.

Предмет дослідження – Чисельне моделювання лазерної ударної обробки.

Мета магістерської роботи – Визначення оптимальних параметрів лазерної обробки для зміцнення поверхні зубчастих коліс авіаційних двигунів.

Методи дослідження та розробки – програмне забезпечення Abaqus для чисельного моделювання ефекту лазерного зміцнення з метою пошуку найбільш раціональних параметрів лазера, програмного забезпечення Pro E для побудови моделі зубчастого колеса, Динамічний явний та статичний неявний алгоритми для аналізу закону розподілу полів залишкових напружень.

Новизна результатів - обґрунтування теоретичних засад використання лазерної обробки для зміцнення авіаційних зубчастих передач.

Практична цінність – моделювання методом скінченних елементів показало, що методика лазерної обробки може бути ефективною застосована для зміцнення поверхневих шарів зубчастих передач авіаційних двигунів для підвищення їх ресурсу та довговічності.

МАГІСТЕРСЬКА РОБОТА, ЛАЗЕРНА ОБРОБКА, ЗУБЧАСТІ КОЛЕСА, ПОВЕРХНЕВИЙ ШАР, ЗМІЦНЕННЯ, МЕТОД СКІНЧЕННИХ ЕЛЕМЕНТІВ

ABSTRACT

Master degree thesis “Numerical simulation of laser shock peening

of aircraft engine gears”

75 p., 29 fig., 3table, 25 references

Object of study – Laser shock peening.

Subject of study – Numerical simulation of laser shock peening.

Aim of master thesis – Determination of laser shock peening optimal parameters for aircraft engine gears surface layers strengthening.

Research and development methods – Abaqus software for numerical simulation of the laser shock peening hardening effect in order to find the most rational laser parameters, Pro E software for building a gear model.

Novelty of the results – theoretical principles substantiation of laser shock peening application for aviation gears strengthening.

Practical value – finite element modeling showed that the laser shock peening technique can be effectively applied to strengthen the aircraft engines gears surface layers and increase their service live and durability.

MASTER THESIS, LASER SHOCK PEENING, ENGINE GEARS, SURFACE LAYER, STRENGTHENING, FINITE ELEMENT ANALYSIS

CONTENT

INTRODUCTION

Gears are one of the important transmission devices in aircraft engines and are also widely used in other aircraft systems. During the service life of gears, the gear tooth surfaces are subject to continuous wear and are prone to tooth fracture. Due to the special shape of gears, many traditional material surface peening techniques such as shot peening and surface rolling peening are not suitable for gears, so a new material peening technique is urgently needed.At the end of the last century, the USA developed a new technology called "laser shock peening" and invested a lot of research to make this technology develop rapidly.The technology has also been successfully applied in the USA in the production and maintenance of aircraft. As there are many factors affecting the results of laser shock peening, it would be costly and expensive to use purely experimental methods to carry out research, whereas finite element simulation methods can well avoid these problems. Therefore, in this paper, the factors and parameters affecting laser shock peening are investigated using finite element software to provide some guidance and basis for the actual laser shock peening process.

The first part of the thesis introduces the background and significance of the research on this topic. Firstly, the principle of laser shock peening technology is introduced. The laser emits a high-energy laser beam that irradiates the absorption layer on the surface of the target material, which absorbs the laser energy and ionises into a large amount of plasma, forming a pressure wave. The pressure wave is transmitted along the depth of the target material to the inside of the target material, forming a residual compressive stress layer on the surface of the target material and refining the internal grains of the material, thus achieving the strengthening effect.

The second part of the thesis introduces the basis of the laser shock peening simulation, determining the target's intrinsic model as the J-C intrinsic model; Creating the gear model through Pro E software; calculating the laser pressure wave using the relevant calculation equations, and then solving the dynamic analysis step solution time based on the created target model. Finally, the mesh size of the gear model was determined by setting different mesh sparsity levels.

The third part of the thesis completes the simulation of four laser parameters. The effects of laser pulse energy, laser spot radius, number of impacts and spot lap rate on the shock peening effect are investigated. Finally, laser shock peening simulations were carried out on a single tooth model of a gear with reasonable laser parameters.

The fourth part of the thesis is devoted to labor protection, which considers the working conditions of laser shock peening technology, analyses possible safety hazards in the laboratory and develops appropriate protective measures as a means of protecting workers from injury during work.

The fifth part of the thesis is on environmental protection.Introducing the Boeing 787's design philosophy to protect the environment, reduce tailpipe pollution, reduce noise and more.Airlines have to consider the protection of the environment when designing their aircraft.

PART 1
LASER SHOCK PEENING TECHNOLOGY FOR AVIATION GEARS

As one of the most commonly used key components in mechanical equipment, gears are generally made of high-strength steel. During the service period, the gears are subjected to alternating bending stress for a long time, so they are prone to fatigue and tooth breakage. As an emerging strengthening technology, laser shock strengthening can form a residual compressive stress layer on the strengthened surface, increase its dislocation density, and refine the grain size, thereby effectively improving the fatigue performance of the gear tooth root. Laser Shock Peening (LSP) is an advanced manufacturing technology developed in the late 20th century, which can generate a residual compressive stress of hundreds of MPa on the surface of the target, thereby improving the fiber hardness, tensile properties, Fatigue resistance as well as wear resistance and stress corrosion resistance, etc.

These methods have some shortcomings, such as uneven surface stress distribution and grain refinement, high cost of strengthening, and imperfect development of strengthening technology. Therefore, it is urgent to find a more perfect gear surface strengthening technology. Laser shock strengthening technology is an emerging surface strengthening treatment process, which is characterized by deep strengthening layer thickness and uniform strengthening effect, which can strengthen small parts, and is very suitable for application on gear tooth surfaces.

The United States is the first country in the world to start researching laser shock strengthening. At the end of the last century, the technology has been successfully applied to aero-engines and achieved excellent strengthening effects. For example, after the engine blades are strengthened by laser shock, the The initiation and propagation of cracks at the edge of the blade body are effectively inhibited.

The gear material used in this project is 18Cr2Ni4WA. In China, many aviation gears are made of this material. It is an excellent carburized steel with high hardenability. After carburizing quenching and low temperature tempering, the surface hardness is very high, and the material center The strength, toughness and plasticity are well matched.

1.1 Research Background

As the "heart" of various types of aircraft, aero-engines play a decisive role in the performance of aircraft. With the rapid development of modern science and technology, people put forward requirements for higher reliability, stronger durability, longer life and lower manufacturing costs for the performance of aircraft. This also indirectly translates into stricter requirements for various performances of aero-engines, and more advanced design concepts and processing technologies should be adopted in the manufacture of engines, so that aero-engine parts can be integrated, long-life manufacturing, structural high strength and reliable comprehensive functions and other directions. The development history of aero-engines can be considered as a process of failure, maintenance failure and re-optimization design. No matter which engine is successfully manufactured and in normal working condition, after working long hours and tens of thousands of flights, it will fail and face scrapping.Even aero-engines that operate normally now will face frequent failures in the future.

In order to ensure the normal operation of the aero-engine, it is necessary to carry out long-term design optimization and test of the engine's transmission system. Gears as a device for transmitting machinery, which are also widely used in aircraft. The gears materials is mostly high-strength steel. The main function of the gear transmission system of the aero-engine is to transmit the power to the various accessories to achieve the normal flight of the aircraft. The engine and aircraft starting system, fuel system, lubricating oil system, hydraulic system and other main accessories are driven by the rotor of the engine through the gear transmission [1]. Gear transmission mostly appears in the form of a gearbox. Figure 1.1 shows the gear reducer of a geared turbofan engine (GTF, Geared TurboFan). The gear box is a common variable speed transmission component of various mechanical equipment. Whether the gear can operate normally will directly affect the operation of the mechanical system. 60% of the failures of the gearbox are caused by damage to the gears, so the normal operation of the gear itself is the premise to ensure the normal operation of the system.

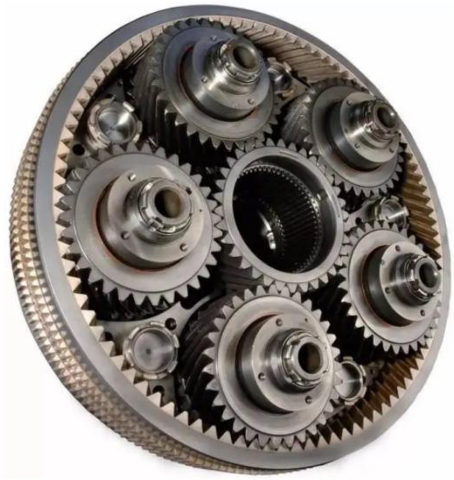

Figure 1.1 - Gear reducer

The gear teeth are subjected to fatigue load during the dynamic meshing process, and fatigue cracks will occur in the high stress area of the tooth root. The failure of the gear caused by the crack propagation will seriously affect the normal operation of the aero-engine. Fatigue cracks appeared in the driving gear of the tail reducer of a certain type of helicopter, which penetrated from the tooth root to the web, resulting in hidden dangers in the transmission system. Wang Xudong et. lists several transmission gear failures that occur during the use of several active aero-engines in and out of the field, and 70% of them are faulty [2]. The failures (gear fractures, rim fractures and axle fractures) are caused by fatigue crack propagation of gears, resulting in serious accidents such as engine idle stop, damage to important parts or aircraft crash [3]. Figure 1.2 shows the gear with broken teeth.

Figure 1.2 - Gear with broken teeth

In the design process of aero-engines, in order to control the overall weight, most of the gears in the transmission system are designed with thin webs and thin rims, and the thickness of the rim is less than or equal to 2.5 times the gear modulus. There are two different types of gear fractures, tooth fracture or rim fracture, the latter of which can lead to catastrophic failure of the gear system.

There are four common failure modes of gears: tooth surface wear, tooth surface fatigue, tooth fracture, and tooth surface plastic deformation. The main reasons of them are:

Tooth surface wear: Poor lubrication and unclean lubricating oil in gear transmission can cause wear or scratches. Wear can be divided into abrasive wear, scratches, corrosion wear and gluing. Abrasive wear and scratches: Abrasive wear and scratches can occur when the lubricating oil is dirty, contains impurity particles, or foreign sand particles in open gear drives, or metal wear debris generated during friction. These external hard particles first embed in one working surface, and then in the form of micro-cutting, dig out the fine particles of metal from the other working surface or cause deformation under plastic flow. In general, the friction at the tip and root is more serious than that at the pitch circle, because the pitch circle is in rolling contact during the meshing process, while the tip and root are in sliding contact. Corrosive wear: The tooth surface is damaged due to the chemical reaction of some chemical substances in the lubricating oil such as acid, alkali or water with the tooth surface to cause metal corrosion.

Ablation: Ablation is the severe wear of the tooth surface due to overload, ultra-high speed, improper or insufficient lubrication, localized high temperature caused by wear, and this temperature increase is enough to cause discoloration and over-aging, or make steel a few microns thick The surface layer is re-fired, and a white layer appears. Tooth surface gluing: high-power soft tooth surface or high-speed and heavy-duty gear transmission, when the lubricating conditions are poor, the tooth surface gluing phenomenon occurs. In the lower pit, in the subsequent meshing transmission, the excess material on this part of the glue can easily cause scratches and grooves on other tooth surfaces, forming a vicious circle.

Tooth surface fatigue: The so-called tooth surface fatigue mainly includes pitting corrosion and spalling of the tooth surface, which is caused by the fatigue of the material.

When the working surface is subjected to alternating stress, microscopic fatigue cracks will be caused on the tooth surface. After the lubricating oil enters the cracks, due to the meshing process, the entrance may be closed first and then squeezed. The lubricating oil in the microscopic fatigue cracks causes the cracks to expand under high pressure. , as a result, small pieces of metal fall off the tooth surface, leaving a small pit, forming pitting. If the fatigue crack on the surface propagates deeper and farther, or a series of small pits are connected due to the failure of the material between the pits, causing large areas or large pieces of metal to fall off, this phenomenon is called spalling. Experiments show that pitting corrosion is a very common form of damage in closed gear transmission. In open gear transmission, abrasive wear always precedes pitting wear due to insufficient lubrication and increased possibility of dirt entering.

Broken gear teeth: When the gear pair is in meshing transmission, the force of the driving wheel and the reaction force of the driven wheel act on each other's gear teeth respectively through the contact point. In a dangerous situation, the contact point is located on the gear teeth at a certain moment. At the top of the tooth, the gear teeth are like a cantilever beam at this time, and the bending stress generated at the root of the tooth is the largest after being loaded. Under the force condition, when the gear teeth are repeatedly loaded, fatigue cracks are also prone to occur due to the phenomenon of stress concentration, and gradually expand, resulting in fatigue fracture of the gear teeth at the root of the teeth.

Plastic deformation of the tooth surface: When the transmission load of the soft tooth surface gear is too large (or under the action of a large impact load), the plastic deformation of the tooth surface is easy to occur. Under the action of excessive friction between the tooth surfaces, the contact stress of the tooth surface will exceed the shear yield limit of the material, and the tooth surface material will enter a plastic state, causing the plastic flow of the tooth surface metal. The tooth surface near the pitch circle of the driving wheel forms a groove, and the tooth surface near the pitch circle of the driven wheel forms a convex edge, thereby destroying the correct tooth shape. Sometimes "flash" can appear on the tooth surface of the driven gear of some types of gears. In severe cases, the extruded metal fills the head gap, causing severe vibration and even fracture.

The traditional gear surface strengthening methods include: surface rolling and extrusion strengthening, surface carburizing or titanium treatment, shot peening, electron beam strengthening, etc. These methods have some shortcomings, such as uneven surface stress distribution and grain refinement, high cost of strengthening, and imperfect development of strengthening technology. Therefore, it is urgent to find a more perfect gear surface strengthening technology. Laser shock strengthening technology is an emerging surface strengthening treatment process, which is characterized by deep strengthening layer thickness and uniform strengthening effect, which can strengthen small parts, and is very suitable for application on gear tooth surfaces.

1.2 Laser shock strengthening technology

Surface strengthening technology is a treatment method to optimize material properties. The traditional processing technologies include shot peening, rolling, low-speed rolling, etc. These processing technologies are widely used in industrial production. Since the first laser appeared in 1960, they have been widely used and are praised by modern industry as "Universal machining tool" and "common machining method for future manufacturing systems" [4], play an active and important role in the field of manufacturing. For example, in the strengthening application of aero-engine blades, the life of the blade can be increased by more than three times, and its surface resistance to foreign body damage can be strengthened [5-7].

Laser shock peening technology has the characteristics of high strain rate, good controllability, uniform strengthening effect, simple and easy-to-control strengthening process, and no thermal effect in the strengthening process [8]. Setting appropriate laser parameters during the shock process will form a uniform residual compressive stress layer on the strengthened surface, and at the same time will refine the internal grains of the material, the resulting residual compressive stress layer depth can reach 1~3mm, and the depth of the stress layer is 5 to 10 times that of mechanical shot peening [9]. The working principle of laser shock peening technology is that high power density (GW/cm2) and short pulse (ns level) laser irradiate the surface of the material, and the surface absorbing layer absorbs the laser energy, fast. Gasification and ionization occur to form high-temperature and high-pressure plasma. The plasma is limited by the confinement layer, and expands and explodes, forming a high-pressure shock wave (GPa magnitude) introduced into the target material [10]. The peak pressure of the pressure wave is greater than that of the material. The dynamic yield strength of the material will lead to a dense, uniform and stable dislocation structure on the surface of the material, and cause it to produce a certain plastic deformation. After the deformation, the surrounding material will be squeezed to form a residual compressive stress layer, while the workpiece is working The tensile stress received will be better offset by the residual compressive stress layer, which will effectively inhibit the occurrence of cracks, thereby improving the overall fatigue life of the material [11].Figure 1.3 is a schematic diagram of laser shock peening.

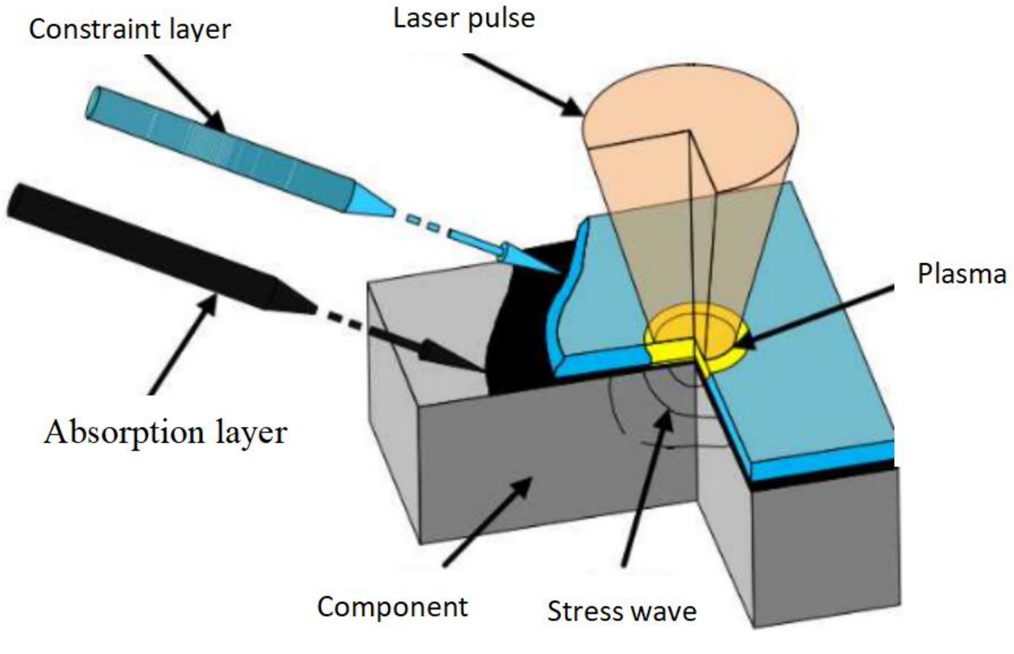

Figure 1.3 - Schematic diagram of laser shock peening

The shock process includes the confinement layer material (usually water or optical glass), the absorption layer material (usually black tape, black paint or aluminum foil) and the target. During the laser shock process, the confinement layer can effectively prevent the plasma from expanding in all directions, and constrain the plasma to move toward the workpiece surface as much as possible, thereby increasing and maximizing the pressure and pulse width of the laser-induced shock wave. In addition, certain requirements must be put forward for the thickness and strength of the constraining layer to prevent the laser from penetrating the constraining layer and causing damage to the machined surface. The confinement layer should also have some physical properties such as high transmittance and acoustic impedance. Wen Deping [12] used water layer, air confinement layer, K9 glass, water film and K9 glass composite layer as the constraining layer material covering the strengthened area in the laser shock treatment process to explore the effect of the above materials on the surface integrity of the workpiece. sexual influence. The test found that the best strengthening effect is the composite layer, followed by the water layer, followed by K9 glass, and the air constrained layer has the worst strengthening effect. When the parts are strengthened by laser shock peening, water is selected as the constraining layer because the water confinement layer is cheap, has good repeatability, and is basically not limited by the dimensions of the parts.

Before laser shock treatment, in order to improve the absorption capacity of laser radiation, increase the peak value of shock wave and avoid melting and vaporization of the metal surface, the surface of the material to be treated must be coated with an absorption (coating) layer [13], generally using aluminum foil, black paint or black tape. The thickness of the absorption layer is one of the important parameters. If the absorption layer is too thin, the laser-induced peak pressure will reduce the plasma density due to insufficient laser-induced peak pressure, and may cause a breakdown phenomenon, which is easy to cause material surface ablation; The vaporized part is attenuated. Ye Yunxia et al. conducted a comparative experiment on the effect of the remaining absorbing layer on the strengthening effect during the laser shock process. The shock wave pressure on the material makes the impact effect worse.

The shock process is as follows: the laser beam emitted by the laser is focused by the lens and then irradiated on the strengthening system. The laser beam passes through the confinement layer and then irradiates the absorption layer material. The absorption layer material absorbs the laser energy and instantly produces a gasification reaction, forming a high temperature with extremely high pressure. Plasma [14], and the plasma cannot expand outward under the restriction of the confinement layer, so it will exert a great pressure on the material below, impact the surface of the material, and continuously propagate stress waves into the material. This is how laser shock peening works.

1.3 Application of laser shock peening technology in aero-engine

In the world, the fatigue fracture of military aero-engine components is also a recognized aviation technology problem, and even the United States, which is very advanced in aviation technology, has suffered heavy losses as a result. In the 1980s and 1990s, the two types of engines equipped with the famous third-generation fighter jets F-15 and F-16 in the United States suffered from many blade breakage failures, causing major flight accidents and seriously affecting flight safety and combat use. . To this end, the United States implemented a high-cycle fatigue national research program in the 1990s, with the goal of improving the high-cycle fatigue design level of components, eliminating aero-engine failures caused by high-cycle fatigue, improving flight safety and reducing operating costs. The High Cycle Fatigue Science and Technology Program divides technical work into 7 action groups: (1) Component Surface Preparation; (2) Material Damage Tolerance Studies; (3) Testing; (4) Component Analysis; (5) Forcing Response Estimation; (6) Passive Damping; (7) Engine Validation (added in 1999). Among them, the Component Surface Treatment Action Group provides coordination and linkages between players working on laser shock peening and related technologies, with the goal of improving the blade leading edge damage tolerance by a factor of 15 (allowing for an increase in crack length from 0.127mm to 1.905mm) . The component surface treatment action group selected from a number of surface strengthening technologies, focusing on the development of laser shock peening technology, as the primary process technology measures, organized Lawrence Livermore National Laboratory, Los Alamos National Laboratory, US Air Force Research Laboratory, GE (General Electric Company), MIC Company (Metal Modification Company) and other units have jointly tackled key problems. After a lot of experiments, the results show that laser shock peening is one of the effective means to solve the high cycle fatigue problem of aero-engine. The ultimate goal of this group is to develop and The ability to achieve production-type laser shock peening that meets the U.S. military's and manufacturers' affordability goals for fatigue-critical parts.

In 1995, Dr. Jeff Dulaney of the United States established the world's first company with laser shock peening technology as its core business, and successfully moved laser shock strengthening technology from laboratory to practical [15].

In 1997, GE established a laser shock peening production line, and successfully carried out laser shock peening experiments on the first-stage fan blades of the F101 engine, and achieved success. The F101-GE-102 engine fan blade has a large depth of residual compressive stress after laser shock peening treatment, which effectively prevents the initiation and expansion of cracks on the edge of the blade body, and its resistance to foreign object damage is increased by 15 times. This technology The application of laser shock peening has changed the original advanced non-destructive testing method to routine visual inspection, which greatly saves high maintenance costs. Relevant institutions have found that the application of laser shock peening can save the US Air Force millions of dollars in military expenses per month. In 1998, American R&D Magazine listed the technology as one of the 100 most valuable new technologies. Subsequently, the technology was gradually extended to more expensive integral components and blades. LSP Technology Company [16-17] first tried the laser shock peening technology of integral blisks, which more than doubled the fatigue strength. The laser shock peengthening process is shown in Figure 1.4.

Fig.1.4 - Laser shock peening processing for bladed disk

From 1998 to 2000, GE Company of the United States applied laser shock peening technology to impact strengthening of F110 and F404 engine fan blades and compressor blades, solved the high cycle fatigue crack fracture problem of F110 and F404 engine fan blades, and made these engines resistant to external conditions. Physical damage ability increased by 15 times.

In 2000, in the late stage of the development of the F119 engine, it was found that its fourth-stage integral blisk resistance to foreign object damage did not meet the requirements of the F/A-22 aircraft, and the threshold value of the stress intensity factor should be increased by at least three times. A lot of time and money. Therefore, PW Company and the U.S. Air Force put forward the technical requirement of using laser shock peening technology to improve the ability of the fourth-stage integral blisk of the F119 engine to resist damage by foreign objects. LSPT and Pratt & Whitney in the United States used laser shock peening technology to process the cracked blisk blade. The material of the blade is Ti6Al4V, the length of the prefabricated crack of the blade is 0.127mm, and the fatigue strength of the original blade is 586.1-689.5MPa. 206.85MPa, which is far lower than the design requirement of the blade (379MPa). After the damaged blade is strengthened by laser shock, the fatigue strength has risen to 413.7MPa. The experiment shows that laser shock peening can more than double the fatigue strength of the notched blisk, which has achieved great success [18]. Replacing the existing blisk will cost tens of millions of dollars, and the development and production schedule will be greatly delayed. The US Air Force licensed LSPT to carry out laser shock peening on the blisk, which greatly reduces the cost and ensures the development and production progress. . Therefore, laser shock peening is listed as one of the key technologies in the development of fourth-generation fighter engines by the United States, which is not only used to improve the damage resistance of blades, but also to improve the high-cycle fatigue strength and damage repair performance of blades.

In 2001, LSP Technology Company of the United States carried out laser shock surface modification processing for the engine blades of R.R. and P&W companies, which is the first case of applying laser shock strengthening technology in commercial aircraft. As of 2011, a total of more than 100,000 blades have been processed, extending the service life of blades several times, reducing maintenance and repair costs, and achieving significant economic benefits.

Since 2002, laser shock peening has been used on a large scale in the United States for the manufacture and repair of aerospace components. After the wedge-shaped root of the blade is strengthened by laser shock, the fretting fatigue life of the blade is increased by at least 25 times. According to MIC, the use of laser shock peening in the production of jet engine blades can improve reliability. Due to the reduction in blade replacement, the US Air Force can save millions of dollars in aircraft maintenance costs and millions of dollars in parts replacement costs every month. It is estimated that the treatment of military engine blades can save more than $1 billion in costs. MIC received the highest achievement award in defense manufacturing in the United States in 2005 due to its contributions to laser shock strengthening. The U.S. Army urgently needs to increase the power of helicopter engines (especially in the high altitude areas of Afghanistan), and the increase in power power requires a substantial increase in the fatigue strength of the main shaft and engine transmission components. In the U.S. Army's manufacturing technology program, laser shock peening is used to treat helicopter power and transmission devices including Apache, Black Hawk and Chinook, which effectively improves the fatigue strength of these components and has been implemented in the production process. Helicopter equipment manufacturers OEM, Sikorsky, Rolls-Royce and Boeing participated in the study, and the U.S. Army Manufacturing Technology Program also funded the Enterprise Innovation Initiative (SBIR) "Laser Peening Life Extension Study for Gunships", which mainly conducted Research on strengthening process of gears and carburized steel for component manufacturing based on proven effectiveness. Figure 1.6 shows the laser shock peening of transmission gears in the United States.

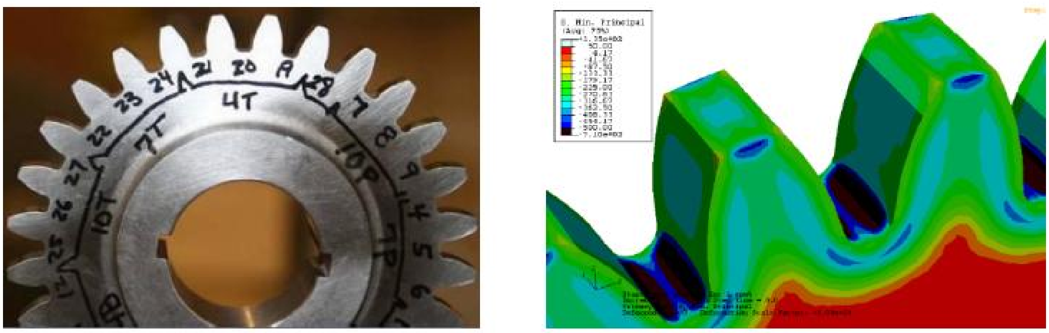

Figure 1.6 - Laser shock strengthening of transmission gears in the United States

In 2003, with the approval of the federal aviation authority (FAA), some parts of Boeing 777 aircraft began to use laser shock surface modification technology. In 2004, the

F119-PW-100 engine's fourth-stage high-pressure compressor integral blisk and other components were officially put into production, and were gradually popularized and applied in other key parts and wearing parts. As of 2009, more than 75% of the blisk workpieces have adopted laser shock strengthening technology.

In terms of aircraft, the United States has built a laser shock peening production line dedicated to the processing of bolt holes for F-22 fighter jets. The value of the production line is as high as 200 million US dollars. Connecting bolt holes between the wing and the fuselage, insufficient fatigue strength is an important life constraint factor. Laser shock peening technology successfully solved this problem. In 2012, American Metal Improvement Company 35 successfully developed vehicle-mounted mobile laser shock peening equipment. It is used to repair the damaged part of the blade during the ground fault inspection, as shown in Figure 1.7. In this way, after the aircraft is flying in the air with blade damage and other faults, measures to suppress crack propagation can be taken immediately after landing, effectively improving the fighter's field integrity rate.

Fig.1.7 - US F-22 fighter laser shock peening site

Due to the remarkable effect of laser shock peening technology, the United States has begun to apply this technology in more aspects. The U.S. Naval Air Vehicle Center (NAWC), MIC Corporation, and Technical Writing Center (CT) jointly used this technology to solve the fatigue fracture problem of carrier-based aircraft landing tail hooks. The US National Laboratory (Lawrence Livemore) has confirmed that the stress corrosion and fatigue crack growth rate of welds can be significantly improved after treatment with laser shock peening technology. The United States used its extensive theoretical basis and application experience accumulated in the late 20th century to promote laser shock peening technology on a large scale, military and strategic significance. At present, the research on laser shock peening has covered different professional fields (aviation blades, carrier-based aircraft hooks, welds of nuclear waste storage containers, etc.) and different materials (stainless steel, titanium alloy, magnesium alloy, aluminum alloy, etc.).

So far, the application of laser shock peening technology in aero-engines has gradually matured, but there are few researches on laser shock peening technology of aero-engine gears, especially gear tooth surfaces. Therefor, the content of this article is to explore the application of laser shock peening technology on gear tooth surfaces.

1.4 Aviation gear materials

Aviation gears are key components of aeroengines. Throughout the flight, the gear drive must operate reliably to ensure that the engine and all aircraft accessories are RPM, steered, and required power as designed. With the continuous improvement of the performance and reliability requirements of aero-engines, the alternating loads and severe impact loads on gears are increasing, the stress is complex, and the working conditions are harsh. Sex and other aspects put forward higher requirements. At present, various types of active engine gears have faults, such as ring gear fracture, gear tooth breakage, tooth surface peeling, etc., resulting in engine damage and aircraft crash accidents. Therefore, it is necessary to improve the selection and processing methods of engine gear materials.

The main feature of aviation gear materials at home and abroad is the use of electroslag or vacuum remelted high temperature alloy steel. The aviation gear materials used in China are mainly 12CrNi3A, 12Cr2Ni4A, 38CrMoAlA, 18Cr2Ni4WA, 20CrNi3A and so on. The processing of these materials into aviation gears requires complex chemical heat treatment, so that the hardness of the core is HRC31 ～ HRC41, and the surface hardness is not lower than HRC60, so that the surface of the gear has a higher hardness, and the core has a certain toughness to adapt to the work of the gear. and the carbon content, organization uniformity, grain size and chemical heat treatment of the surface layer are strictly specified [19].

In recent years, China's engine technology has continued to improve, the design and processing technology of gears have also continued to improve. 18Cr2Ni4WA steel is widely used in gear materials. It is an excellent carburizing steel with high hardenability. After carburizing and quenching After adding low temperature tempering, the surface hardness is very high, and the strength of the core is well matched with toughness and plasticity. Therefore, 18Cr2Ni4WA is selected as the gear material in this paper. Figure 1.8 is an aero-engine gear made of 18Cr2Ni4WA material.Its metallographic structure is acicular martensite, as shown in Figure 1.9.

Figure 1.8 -18Cr2Ni4WA gear

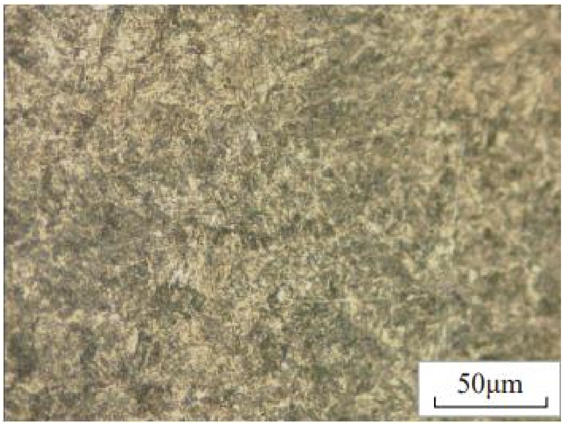

Figure 1.9 - metallographic structure

18Cr2Ni4WA belongs to high chromium alloy structural steel (GB/T3077-1988), its main chemical composition is: C element content is 0. 13%~0. 19%, Si element content is 0. 17%~0. 37%, Mn Element content is 0. 30%~0. 60%, Cr element content is 1. 35%~1. 65%, Ni element content is 4. 00%~4. 50%, W element content is 0. 80%~1. 20 %, the allowable residual content of S element, P element and Cu element does not exceed 0.025%. The heat treatment process includes quenching: the heating temperature is 950 ℃ for the first time, 850 ℃ for the second time, and the cooling method is oil cooling; tempering: heating temperature 200 ℃, the cooling method is water cooling or air cooling. The performance parameters of 18Cr2Ni4WA material are shown in Table 1.1:

Table 1.1-18Cr2Ni4WA performance parameters

Density(kg/cm^3)	Elastic Modulus(N/cm^2)	Poisson's Ratio	Yield Strength(N/m^2)	Tensile Strength(N/m^2)
7.91	2.02×10^{11}	0.27	8.35×10^{8}	1.18×10^{9}

Conclusion to the part 1

Laser shock peening technology is the world's most advanced material surface processing technology. It is widely used in many fields and has a huge potential market and broad development prospects. Laser shock peening technology is a mechanical effect that utilizes laser-induced plasma shock waves. Compared with the traditional laser processing technology, the new technology for modifying the surface of the material has almost no thermal effect on the material; compared with the traditional surface modification technology, it can introduce a deeper residual compressive stress layer on the material surface and improve the material resistance fatigue performance, with technical advantages such as more strengthening effect, good applicability, and strong controllability. Since the end of the last century, the United States has carried out a series of research programs on laser shock peening technology, and vigorously developed the application of laser shock peening technology in aircraft parts. Due to the special shape of the gear, it is different from other rod-shaped materials and plate-shaped materials. It is relatively difficult to process and strengthen it, especially the tooth surface of the gear. The tooth surface area is narrow and small, and the laser shock peening technology can process and strengthen the tooth surface of the gear very well. The correct application of laser shock peening technology in the processing of aero-engine gears can greatly extend the service life of the gears. However, there are still many problems to be solved on how to apply this technology to aviation gears. Therefore, in this paper, gears made of 18Cr2Ni4WA material are selected as the research object to explore the finite element analysis and experimental research of laser shock peening of aviation gears.

PART 2

FUNDAMENTALS OF LASER SHOCK PEENING SIMULATION

Laser shock peening is a new and efficient material surface treatment technique developed at the end of the twentieth century. Traditional experimental methods are difficult to obtain the changes in physical quantities such as internal stresses, energy and residual stresses in the direction of the depth of the material layer after peening and their specific values.This problem can be solved by means of finite element simulation, which can easily extract the variation law of each physical quantity with time and space from the model, and thus analyze the factors affecting the laser shock peening.The finite element simulation study is based on the physical and chemical properties of the material, establishing the intrinsic model of the material and refining the mesh, loading the laser shock wave model, setting the relevant boundary conditions, and calculating through the simulation software to obtain the change law of the corresponding process to guide the experimental research. Compared with experimental studies, simulation studies require a higher theoretical foundation, shorter computational cycles and lower costs, so it is necessary to use a combination of simulation and experimental methods.Some key fundamental issues need to be addressed before laser shock peening finite element simulations can be performed. In this part, the key factors affecting laser impact strengthening simulations are analyzed and studied, including material intrinsic model, target material model, laser pressure wave size, mesh size, and analysis step time.

2.1 Material intrinsic Model

The gear material chosen for this paper is 18Cr2Ni4WA, which was introduced in Chapter 1.The material intrinsic model is the physical basis for numerical simulations to analyse the dynamic response mechanism of the target material. The selection of the correct material intrinsic model is very important for the finite element simulation results and is a more reliable guide for experiments.Commonly used material instantiation models in China include the ideal elastic-plastic model (yield strength is dynamic yield strength), the Zerilli-Armstrong instantiation model and the Johnson-Cook instantiation model [20].The material can achieve strain rates of 10^5-$10^7 s^{-1}$ during laser shock peening. The ideal elastic-plastic model does not take into account the effects of cold work hardening of the material, only the yield limit, that is, as long as the impact pressure reaches the yield limit of the material will be plastic deformation, if less than the yield limit on the value of the elastic deformation. The Zerilli-Armstrong model has high parameter requirements that must be obtained through multiple trials, increasing the cost of numerical simulations and making the simulation period longer.The Johnson-Cook model combines the advantages of both models, taking into account not only the effects of cold work hardening and strain rate, but also ignoring the effects of deformation and impact pressure, making the parameters easier to obtain and no less accurate.The Johnson-Cook model is very suitable for high strain rate loading conditions and is in line with the process characteristics of laser shock peening. Therefore, the Johnson-Cook model is used to complete the numerical simulation of laser shock peening. The relevant parameters of the J-C model for the material are shown in Table 2-1:

Table 2-1 Table of model parameters for 12Cr2Ni4WA

A (MPa)	B (MPa)	C	n	ε_0
1010	1409	0.04	0.67	1

2.2 Target material model

The simulation process of laser shock peening simulation is to use the pressure instead of laser shock wave to act on the target model, the stress wave generated by the laser action will propagate from the target surface to the internal direction until the model boundary, then the stress wave will be reflected at the boundary to enter the model, which must lead to inaccurate calculation results, so it is necessary to establish an infinite cell area around the model to prevent the reflection of the stress wave.In order to reduce the calculation time and improve the efficiency of the simulation, a symmetric model of the 1/4 target can be established, as shown in Figure 2.1, with symmetric boundary conditions on the two axisymmetric sides of the model, and the bottom and the rest of the sides can be set as fixed constraints. The finite element target model is a square with a side length of 5mm, and the infinite element region also has a side length of 5mm.

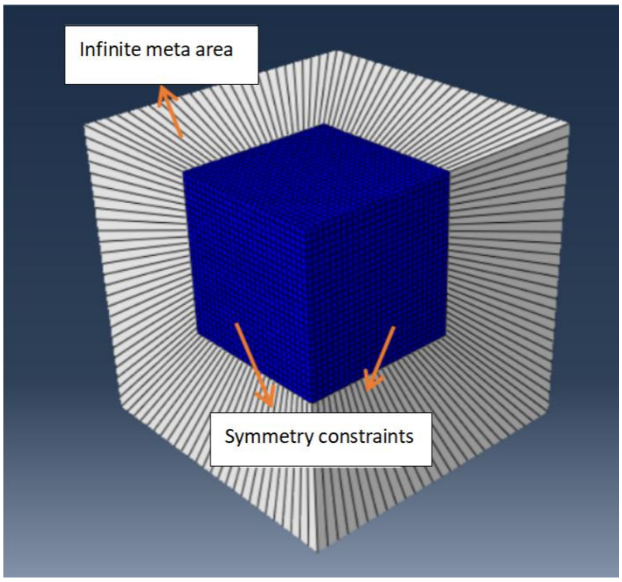

Figure 2.1 - Model of the target material

2.3 Laser shock wave pressure model

The principle of laser shock peening is that the laser emits a high power laser beam that radiates the surface of the target and the absorbing layer on the surface absorbs the laser energy, forming a large amount of plasma.Therefore, shock wave pressure conversion calculations between the laser and the absorber layer must be performed. The Fabbro laser pressure conversion model is currently used internationally [21],The model has three assumptions: (1) The laser power density in the laser shock region is uniformly distributed and the temperature in this region is uniformly increasing. (2) Both the confining layer material and the reinforced material are regarded as isotropic substances. (3) The plasma produced by the laser interaction with the absorber layer expands only in the direction of the target material [22].The specific expressions are given in Eqs. 2-1, 2-2 and 2-3.

$$I(t) = P(t)\frac{dL(t)}{dt} + \frac{3}{2\alpha}\frac{d}{dt}[P(t)L(t)] \tag{2-1}$$

$$\frac{2}{Z} = \frac{1}{Z_1} + \frac{1}{Z_2} \tag{2-2}$$

$$\frac{dL(t)}{dt} = \frac{2}{Z}P(t) \tag{2-3}$$

In the above equation, I(t) is the laser power density as a function of time, P(t) is the laser shock wave pressure as a function of time and L(t) is the plasma generated by the laser shock wave as a function of time an. α is the coefficient of conversion of internal energy into thermal energy during the shock. Z, Z_1, Z_2 are synthetic acoustic impedance, target acoustic impedance, and constrained layer acoustic impedance respectively.From equations 2-1,2-2 and 2-3, the formula for the maximum value of laser shock wave pressure can be derived as follows：

$$P_{max}(GPa) = 0.01\sqrt{\frac{\alpha}{2\alpha+3}}\sqrt{Z(g \cdot cm^{-2} \cdot s^{-1})}\sqrt{I(GW \cdot cm^{2})} \tag{2-4}$$

A review of the literature shows where α is taken as 0.1, the acoustic impedance of the target material $Z_1 = 4.34 \times 10^6 g \cdot cm^{-2} \cdot s$,the acoustic impedance of the confining layer $Z_2 = 2.39 \times 10^6 g \cdot cm^{-2} \cdot s$,and the synthetic acoustic impedance $Z = 4.53 \times 10^6 g \cdot cm^{-2} \cdot s$ [23].The laser pulse energy *I* is calculated as follows：

$$I = \frac{4\gamma E}{\tau \pi d^2} \tag{2-5}$$

In this equation, *E* is the single pulse energy, γ is the effective laser action coefficient on the target, τ is the laser pulse width and *d* is the laser spot diameter. As the maximum single pulse energy of the laser shock peening equipment used in this paper is 8J, the pulse width is 20ns, the spot radius is 2mm, the absorption layer is black tape, γ= 1.5, so I_{max} = 3.183 (GW/cm^2), by the formula (2-4) and (2-5) can be calculated as P_{max} = 6.713GPa.

Yao improved Fabbro's model in that the stress and distance from the spot centre conform to a Gaussian distribution, with the maximum stress value located at the centre of the spot, and the stress value varies with distance from the spot centre, the closer the distance from the spot centre, the greater the stress value. The stress value at any moment and at any point can be calculated by equation (2-6) [24],

$$P(r,t) = P(t)exp(-\frac{r^2}{2R^2}) \tag{2-6}$$

P(t) is the stress value at moment t of the laser pulse action in *GPa*; *r* is the distance from the centre of the spot in mm; *R* is the spot diameter in mm, $exp(-\frac{r^2}{2R^2})$ is the spatially distributed function of the pressure wave.

2.4 Dynamic analysis step solving time

In the process of finite element simulation, the dynamic analysis step time is an important factor that directly affects the simulation results. Too short a time duration will affect the residual waves of the previous shock wave, which will superimpose or cancel each other, resulting in less reliable simulation results, while too long a time duration will prolong the simulation time and reduce the simulation efficiency. From the results of other studies, it is clear that after the kinetic energy of the model has reached zero and the internal energy has established, the internal stress state will also establish, so this can be used as the solution time for the dynamic analysis step.

In order to determine the length of time for the dynamic analysis step of the target, a laser beam with a laser pulse energy of 8J and a spot radius of 2 mm was used to shock the target model for finite element analysis. Figure 2.2 shows the cloud plot of the result after the impact, intercepting the cloud plot of the stress change in the model after the pressure wave acts for 334ns, 668ns, 1000ns, 3000ns and 6000ns. Figure (a) shows the 334 moment; Figure (b) shows the 668ns moment; Figure (c) shows the 1000ns moment; Figure (d) shows the 3000ns moment; Figure (e) shows the 6000ns moment. From the figure, we can see that after the laser pressure wave acts for 300ns, the pressure wave propagates from the surface layer to the inner part of the model, and the maximum pressure value is 9.725GPa at this time. Continuing to propagate down the pressure value gradually decreases, at 1000ns the pressure wave propagates to the boundary between the finite element and infinite element regions and begins to enter the infinite element region, then the pressure wave propagates without reflection in the infinite element region, while the conversion and balance of energy is carried out in the finite element region, at 6000ns the internal energy has established. The equation for the conversion relationship between the various energies within the target is (2-7), W_k is the total external work, E_K is the kinetic energy, E_i is the internal energy and E_v is the viscous dissipative energy.

$$W_k = E_k + E_i + E_v \tag{2-7}$$

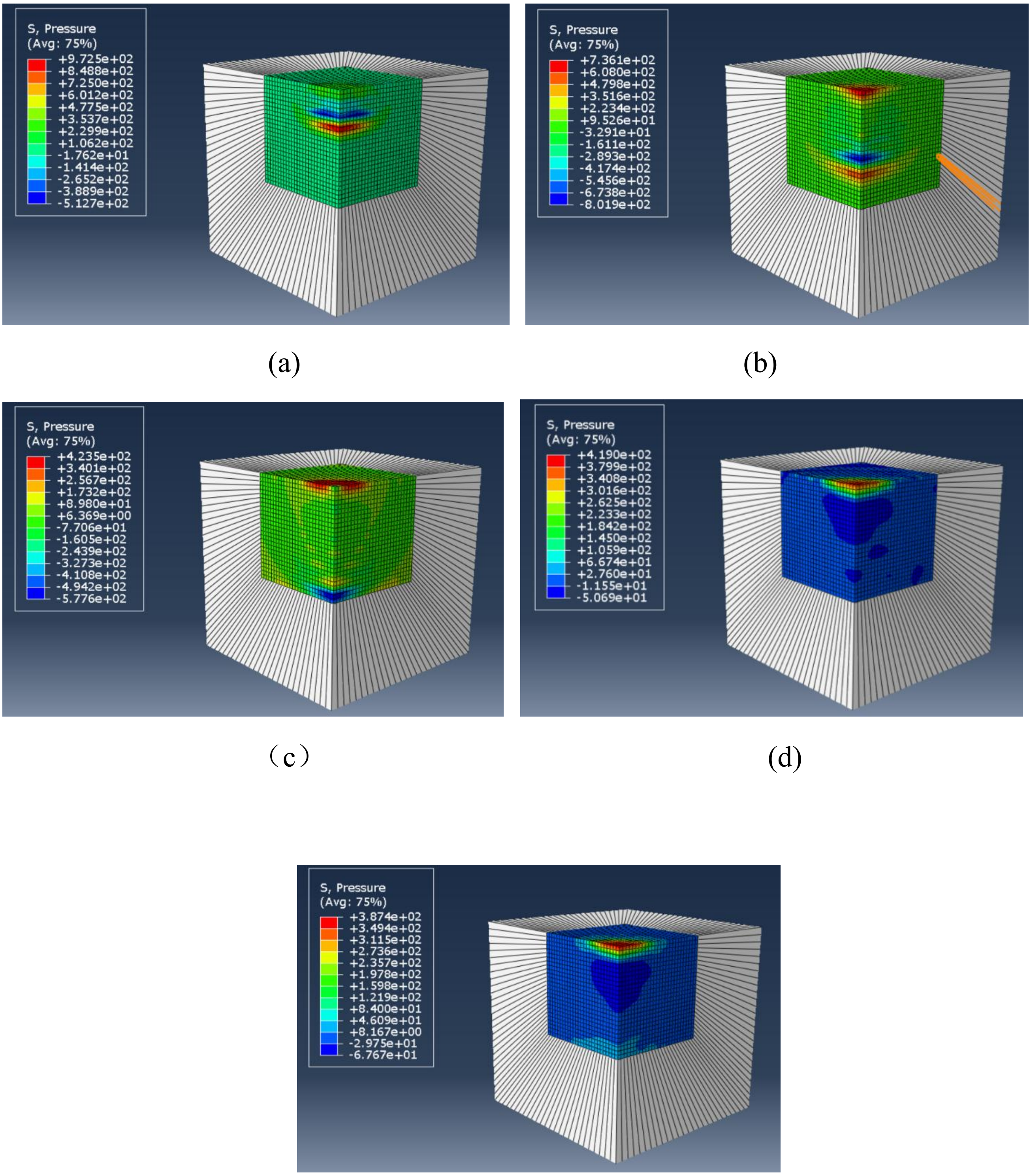

Figure 2.2 - Pressure wave cloud at some moments after laser shock peening

Figure 2.3 shows the energy change curve inside the target after a single point shock on the target, after being subjected to laser shock wave, the total work of the external force is gradually transformed into kinetic and internal energy due to the elastic-plastic deformation inside the target. After a period of time, the internal plastic deformation of the target material is in a stable state, while the increase of viscous dissipation energy makes the kinetic energy and internal energy gradually decrease, and finally part of the internal energy becomes elastic-plastic deformation properties stored, and the kinetic energy gradually decreases to zero. It can be seen from the graph that at 6000ns, the kinetic energy inside the target is zero and the internal energy is stable, so 6000ns is used as the solution time for the dynamic analysis time.

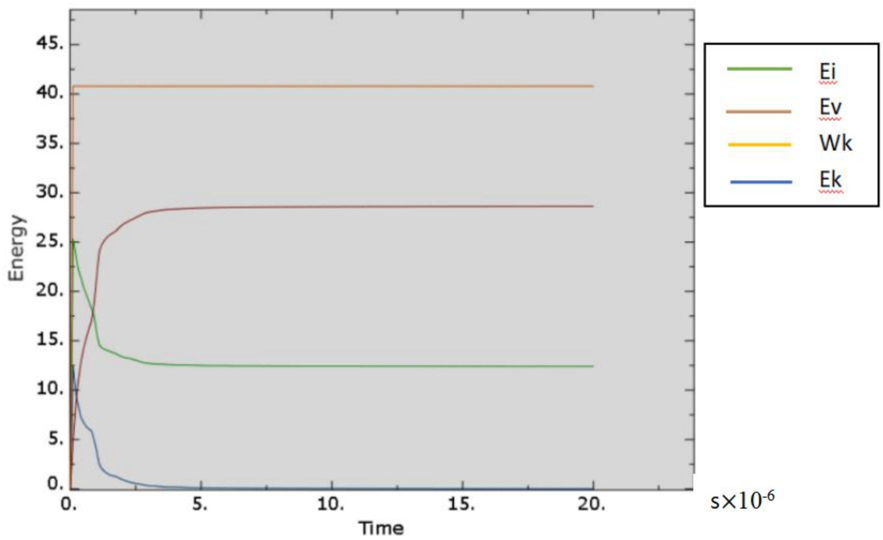

Fig. 2.3 - Energy variation curve inside the target

2.5 Mesh size selection

In this section, the gear model is meshed and the optimum mesh size is selected. The object of study in this paper is the gear tooth surface so the gear model can be simplified to a single tooth and the single tooth model of the gear established is shown in Figure 2.4. Laser shock peening finite element simulation process has high requirements on the model of the mesh division, the degree of mesh sparsity will obviously affect the simulation results, the denser mesh calculation results are more accurate, but will increase the calculation time, so need to balance the mesh size and calculation time.

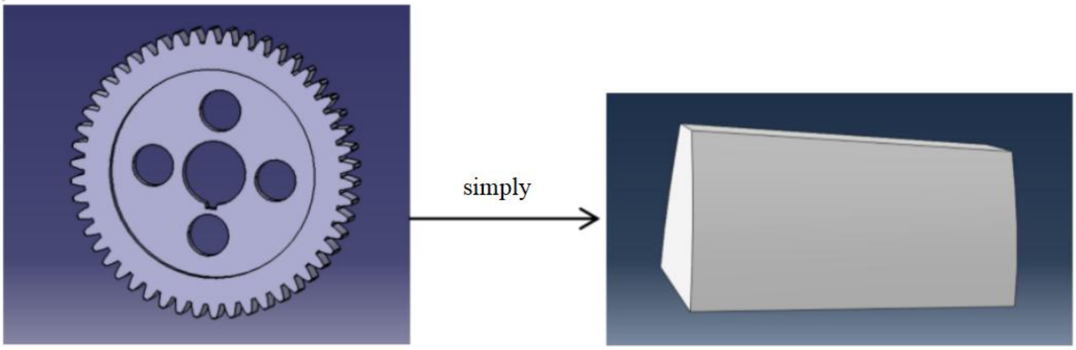

Fig. 2.4 - Gear model

A single point laser shock model was used with a laser shock wave pressure of 6.731GPa, pulse energy of 8J, pulse width of 20ns and spot radius of 2mm. Since the process of laser shock peening involves the propagation of the laser generated pressure wave from the surface of the model to the interior (the longitudinal direction of the model), the longitudinal grid size is first fixed at a smaller size than the computer can handle, while the transverse grids are set at 100μm、150μm、200μm、250μm、300μm、350μm、400μm and 450μm respectively. The results are then calculated and plotted as a residual stress curve, as shown in Figure 2.5. It can be seen from the graph, as the transverse grid becomes larger, the residual compressive stress begins to drop at 2mm from the centre of impact (at the edge of the spot), due to the "residual stress voids" that appear here.The "residual stress cavity" is a shear stress wave that is generated at the edge of the spot when it is reinforced by a circular spot laser impact, which causes a reverse plastic strain at the centre of the impact and thus reduces the residual stress. Therefore, 100μm was chosen as the transverse dimension of the grid.

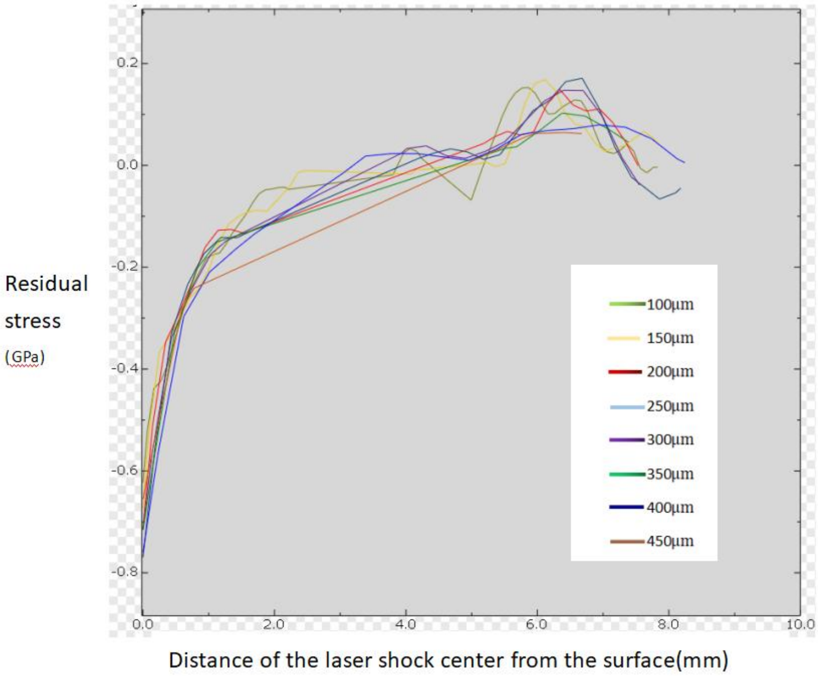

Fig. 2.5 - Comparison of residual stress profiles for each transverse grid size for the longitudinal grid of 100μm

The transverse grid size was set to 100μm and the longitudinal grid was set to 100μm、150μm、200μm、250μm、300μm、350μm、400μm and 450μm in that order. After submitting the calculation, the magnitude graph of the residual stress in the centre of the laser impact along the depth direction was extracted and shown in Figure 2.6. It can be seen from the graph that the residual stresses tend to stabilise after the longitudinal grid size reaches 150μm, and that reducing the grid size has little effect on the residual stress values. Therefore, in order to improve the efficiency of the calculation, the size of the longitudinal grid can be set to 150μm.

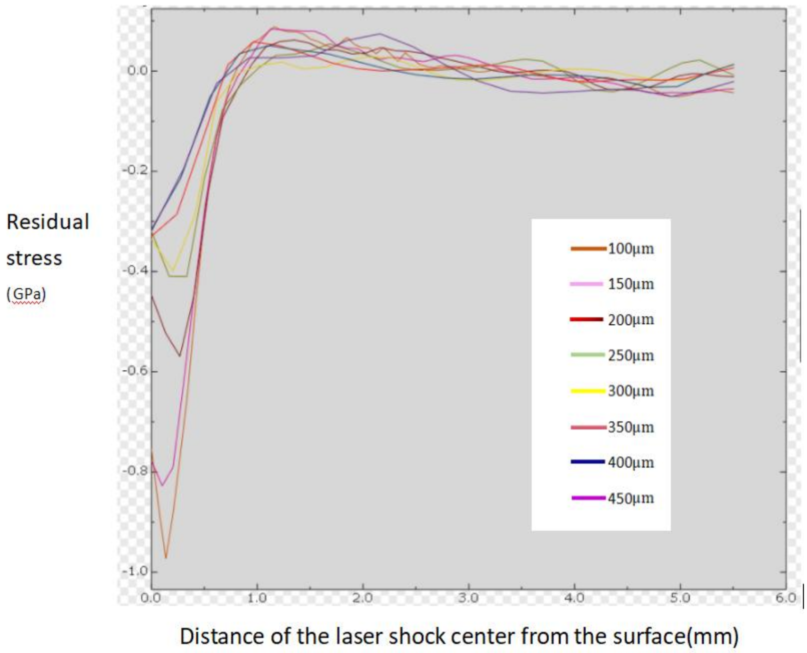

Fig. 2.6 - Comparison of residual stress profiles at each longitudinal grid size for the transverse grid of 100μm

Conclusion to the part 2

The second part addresses the fundamental issues of laser shock peening finite element simulation of gear models. The gear material is 18Cr2Ni4WA, which has a strain rate of 10^5-10^7 s^{-1} during laser shock peening, and the Johnson-Cook model is very suitable for high strain rate loading conditions, which is in line with the process characteristics of laser impact strengthening, so the Johnson-Cook model is used as the intrinsic model of the target material. The maximum pressure of the pressure wave model is 6.713GPa. In order to save simulation time and improve simulation efficiency, a symmetric model of the 1/4 target can be established. On this target model, a single point laser impact is applied to strengthen the target. The analysis of the results of the single point laser shock on the target model and the graph of the energy change inside the target can be determined as a 6000ns analysis step. Finally, the optimum mesh density for the target model can be obtained by varying the transverse and longitudinal mesh sizes in turn, and the transverse mesh set to 100 μm and the longitudinal mesh set to 150 μm .The determination of the above factors provides the basis for subsequent accurate finite element simulations of laser shock peening.

PART 3

NUMERICAL SIMULATION OF LASER SHOCK PEENING

Laser parameters are important factors influencing the effectiveness of laser impact peening. In this section, four factors - laser pulse energy, spot radius, spot lap rate and number of impacts - are analysed in simulations and the effect of each factor on the peening results is investigated to determine the optimum laser parameters.Finally the selected laser parameters are used to simulate the partial shock peening of the gear tooth face, laying the theoretical foundation for the strengthening tests of the solid gear tooth face.The size of the laser pulse energy will directly affect the shock peening effect, the laser pulse energy is too small will lead to poor strengthening effect, the formation of residual compressive stress layer depth thickness is small, can not achieve the desired strengthening effect, if the laser pulse energy is too large, although it will improve the strengthening effect, but the laser will ablate the material, damage the workpiece, which is also not the desired strengthening results, so the simulation of different laser pulse energy must be carried out to determine the best laser pulse energy.The value of the spot radius will also have a direct impact on the size of the laser pressure wave, so detailed simulations of the spot radius are required to determine the most reasonable laser spot radius.

3.1 Influence law of different laser pulse energies

The model used for the simulations in this section is the single tooth model shown in Figure 2-4. The laser pulse energies are set to 2J, 4J, 6J and 8J. The pressure wave values for each energy can be calculated using equation (2-4) as shown in Table 3-1.

Table 3-1 Pressure waves for each laser pulse energy

Laser energy(J)	2	4	6	8
pressure wave	3.356	4.747	5.813	6.713

The spot radius of the laser is set to 2mm and the tooth is shocked at a single point, imported into the finite element software and submitted to the task to obtain the results of the calculation.

Figure 3.1 shows the residual stress distribution from the centre of impact to the edge of impact on the impact surface for each laser pulse energy. It is clear from the graph that the minimum residual compressive stress is 0.41GPa for a laser pulse energy of 2J and the maximum residual compressive stress is 0.61GPa for a laser pulse energy of 8J. As the laser pulse energy increases, the residual compressive stress increases, but the difference in the magnitude of the residual compressive stress at the edge of the laser spot (2mm) is very small. It can also be seen in the diagram that the laser pulse energy 2J single point impact has the greatest impact range, reaching 4mm, but the magnitude of the resulting residual pressure is far from that of the pulse energy 8J.

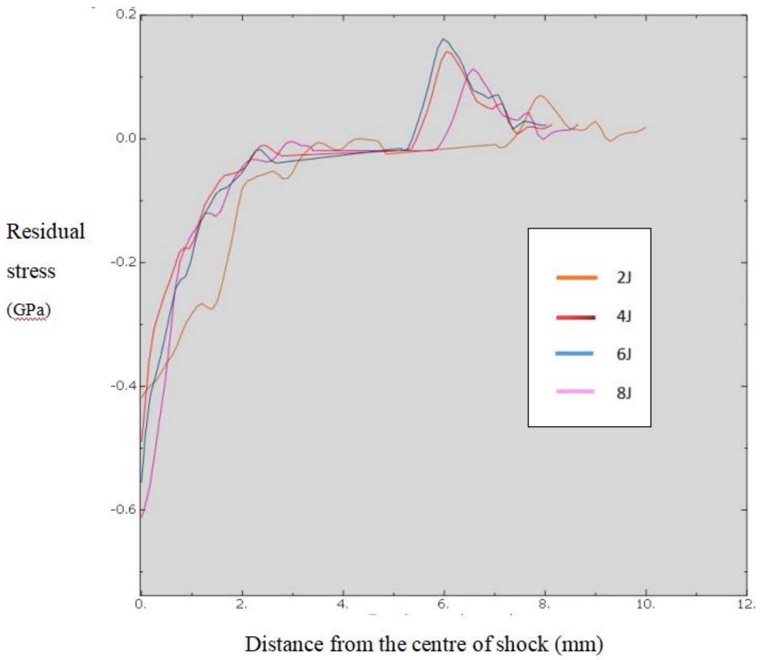

Fig. 3.1 - Surface residual stress distribution curves under different pulse energy shock peening simulations

Figure 3.2 shows the residual stress distribution curve in the depth direction of the layer in the central region of the laser single point impact, from which it can be seen that as the laser pulse energy increases, the residual stress on the surface of the target material and in the depth direction also increases. The depth of the residual compressive stress layer also increases. A laser pulse energy of 2J produces a residual stress depth of approximately 0.5mm and a residual stress of approximately 0.41GPa; A laser pulse energy of 8J produces a residual stress depth of approximately 0.8mm and a residual stress of approximately 0.82GPa. It can also be seen from the graph that the maximum residual stress produced by the laser pulse energy of 6J is 0.88GPa, and is greater than the residual stress produced by the pulse energy of 8J, and with the increase in pulse energy, the residual stress no longer increases, which indicates that when the pulse energy reaches 8J the plastic deformation of the target caused by the laser reaches saturation, and can not continue to make the residual stress increase. The maximum residual stress generated by the pulse energy of 8J occurs in the subsurface layer, indicating the occurrence of a "residual stress hole phenomenon", which becomes more pronounced as the energy increases, because the increase in energy leads to a greater inverse plastic strain at the centre of the impact caused by the shear stress wave [25], resulting in a reduction in the residual stress value at the centre.As can be seen from the above, an appropriate increase in pulse energy can increase the depth of the residual stress layer and thus improve the strengthening effect.

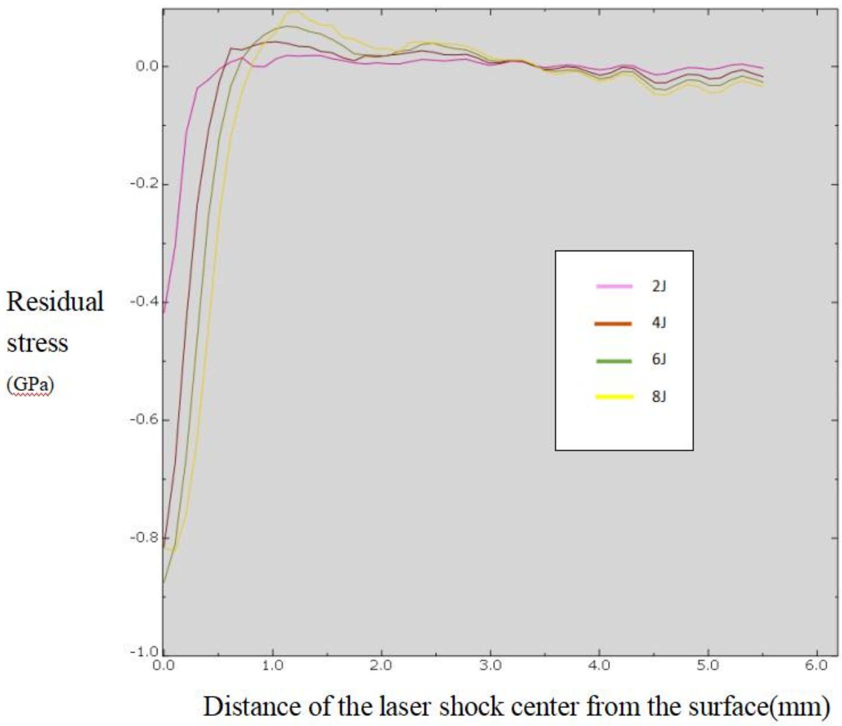

Figure 3.2 - Residual stress distribution curves in the direction of the layer depth at the centre of impact for different pulse energy shock peening simulations

3.2 Simulation of impacts with different laser spot radius

Among the factors affecting the effect of laser shock peening, the spot radius must also be simulated and analyzed. Using Figure 2.4 gear single tooth simulation model with a pulse energy of 8J and an impact count of 1, the spot radius were set to 1mm, 1.5mm, 2 mm, 2.5mm and 3mm, respectively. And then the effect of different spot radii on the impact strengthening results under single point laser impact strengthening was explored.

Figure 3.3 shows the residual stress distribution curves on the impact surface for different spot radius. As can be seen from the figure, increasing the spot radius with the other laser parameters unchanged results in a larger residual compressive stress on the surface, with the maximum compressive stress value increasing from 0.48GPa at a radius of 1.5mm to 0.86GPa at a radius of 3mm.The graph also shows that as the spot radius increases, the area affected by residual stresses also gradually increases, up to 3.1mm at a spot radius of 3mm. The results show that increasing the spot radius can improve the strengthening effect.

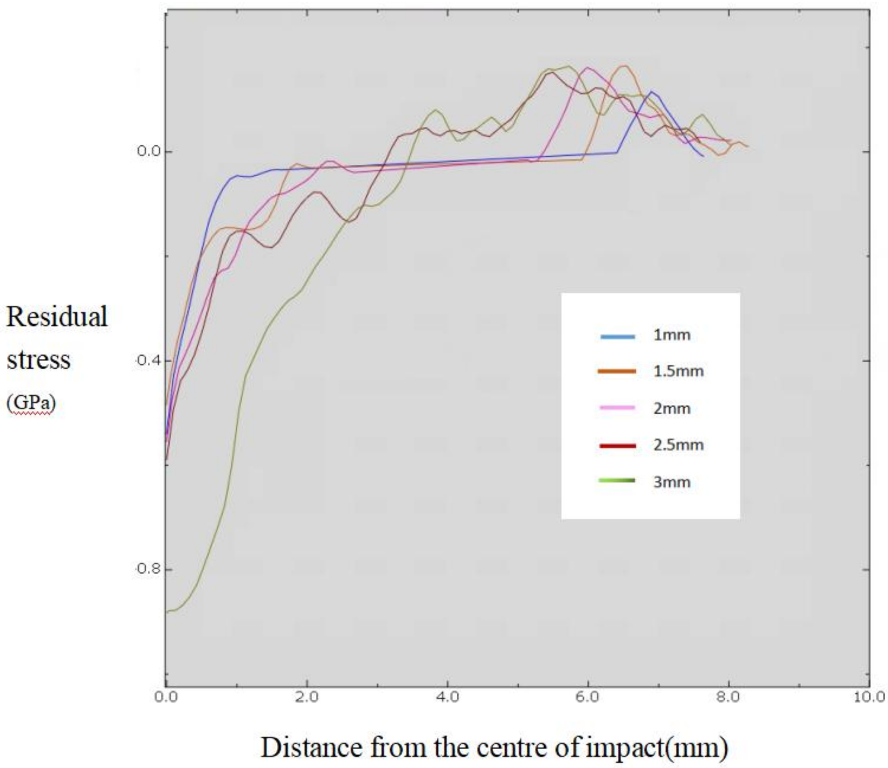

Fig. 3.3 - Residual stress distribution curves on the surface of the impact centre for different spot radius shock simulations

Figure 3.4 shows the residual stress distribution curve at the centre of the laser shock peening in the direction of the layer depth for different spot radius. It can be seen from the figure that as the spot radius increases, the residual stress values at the surface and in the layer depth direction at the centre of the impact gradually increase, with the maximum value of the residual stress increasing from 0.77GPa for a spot with a spot radius of 1 mm to 0.84GPa for a spot radius of 3mm.The depth of the residual stress layer also increases gradually, from a thickness of 0.3mm at a spot radius of 1 mm to a thickness of 0.8mm at a spot radius of 3 mm.When the spot radius is less than 0.25mm, it can be seen from the graph that the maximum residual compressive stress appears in the sub-surface layer of the target material, and the smaller the spot radius the more obvious this phenomenon is. This is because when the spot radius is reduced, the laser energy density will increase rapidly, resulting in the induced pressure wave is much higher than the yield strength of the material surface, making the material surface spot edge to produce a very strong sparse wave, which will lead to reverse plastic deformation of the material at the centre of the impact, thus weakening the surface residual compressive stress.

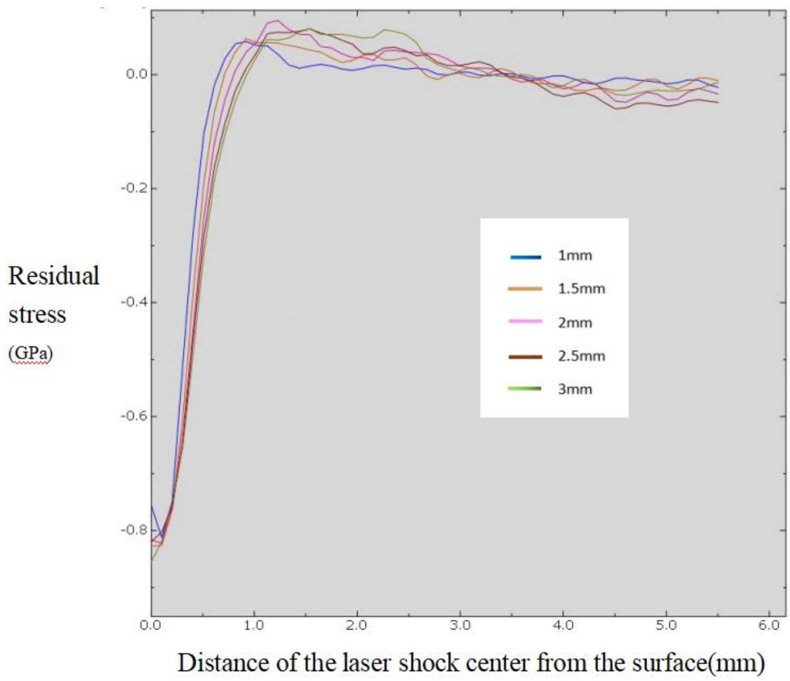

Fig. 3.4 - Residual stress distribution in the direction of the layer depth at the centre of impact for different spot radius shock peening simulations

Combining Figure 3.3 and Figure 3.4 it can be concluded that an appropriate increase in the laser spot radius will not only increase the magnitude of the residual pressure on the target surface, but also the depth of the residual stress affected layer.

3.3 Simulation of single point impact with different number of laser impacts

The same gear single tooth simulation model shown in Figure 2.4 was adopted, keeping the laser spot radius at 2mm and the laser pulse energy at 8J constant, and varying the number of impacts from 1 to 5 times to investigate the effect of the number of impacts on the strengthening effect under the effect of single point laser shock peening.

Figure 3.5 shows the residual stress curve on the impact surface for different number of impacts, from which it can be seen that, with other laser parameters kept constant, the residual stress at the centre of the impact increases with the number of impacts, with the residual stress increasing from 0.55GPa for one impact to 0.74GPa for five impacts.It can also be seen from the graph that when the number of impacts reaches 3 and then continues to increase the number of impacts, the increase in the value of the residual compressive stress is very small, this is because at this time the plastic deformation of the target material reaches saturation and cannot make the residual compressive stress continue to increase.

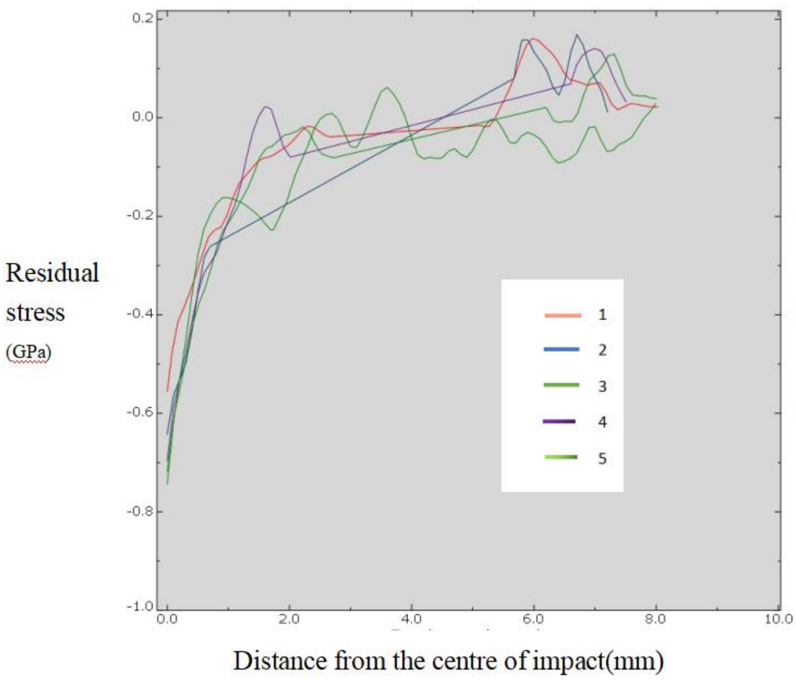

Fig. 3.5 - Surface residual stress distribution curves for different number of impacts under strengthening simulation

Figure 3.6 shows the residual stress distribution curve in the direction of the depth of the impact centre layer for different numbers of impacts, from which it can be seen that when the number of impacts increases, the maximum residual compressive stress value also increases, from 0.80GPa for 1 impact to 1.10GPa for 5 impacts.In the direction of the target layer depth, the influence layer depth also increased from 0.5mm to 1.1mm, but each time the increase in the amount of gradually decreasing, with the increase in the number of impacts "residual stress cavity" phenomenon also appeared at the same time, the residual compressive stress at the centre of the impact continues to weaken.

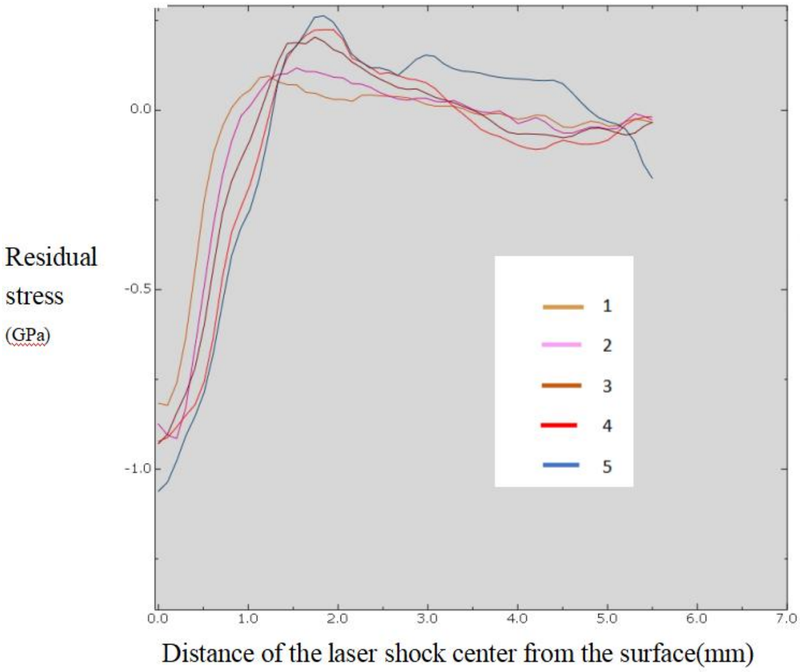

Figure 3.6 - Residual stress distribution curves in the direction of the layer depth at the centre of impact for different number of impacts in intensive simulations

Therefore, according to the simulation results, it is possible to increase the number of impacts to improve the residual compressive stress values, but not to increase the number of impacts too much, as this would lead to poor strengthening results.

3.4 Simulation of laser shock peening with different laser spot lap rates

In the actual production process, the single spot reinforcement effect generally can not meet the overall structural strengthening needs, so the need for continuous laser shock peening. Laser spot lap rate is an important parameter for continuous laser shock peening, the selection of a reasonable spot lap rate can improve the strengthening effect.The laser lap rate η is calculated as in equation (3-1).

$$\eta = (1-L/2R) \times 100\% \tag{3-1}$$

In the equation, *L* is the distance between the centres of two adjacent spots and R is the spot radius. If the laser spot lap rate is 0%, L = 2R; if the laser spot lap rate is 25%, L = 3R/2; if the laser spot lap rate is 50%, L = R; if the laser spot lap rate is 75%, L = R/2. Figure 3.7 shows a schematic diagram of the spot positions at each spot lap rate for a laser radius of 2mm. The distances of the adjacent spots are 4mm, 3mm, 2mm and 1mm respectively.The model used is the single tooth simulation model of a gear shown in Figure 2.4, using a continuous three-point shock peening method (shock sequence from left to right one by one) with a laser pulse energy of 8J and a laser spot radius of 2mm.

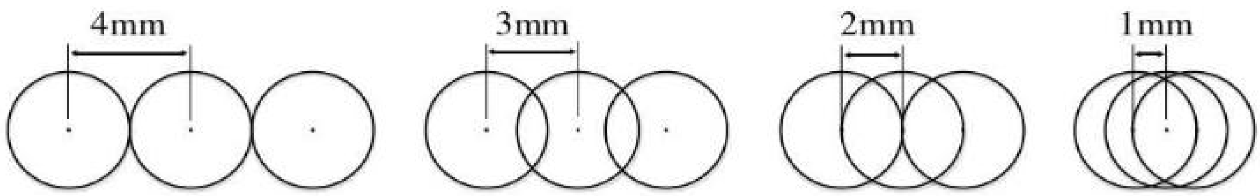

Fig. 3.7 - Spot distribution for spot radius of 2mm at 0%, 25%, 50% and 75% spot lap rates respectively

Figure 3.8 shows the residual stress distribution curves on the impacted surface after simulation for laser spot lap rates of 0%, 25%, 50% and 75% respectively.The graph shows that when the spot lap rate is 0% and 25%, the residual stress curve on the reinforced surface "jumps" and the residual compressive stress is very unevenly distributed. The surface residual stress distribution curves are smoother for spot lap rates of 50% and

75%. In actual reinforcement production the 50% lap rate is usually sufficient to meet the reinforcement quality requirements as the lap rate used in production is significantly longer due to the increased lap rate.

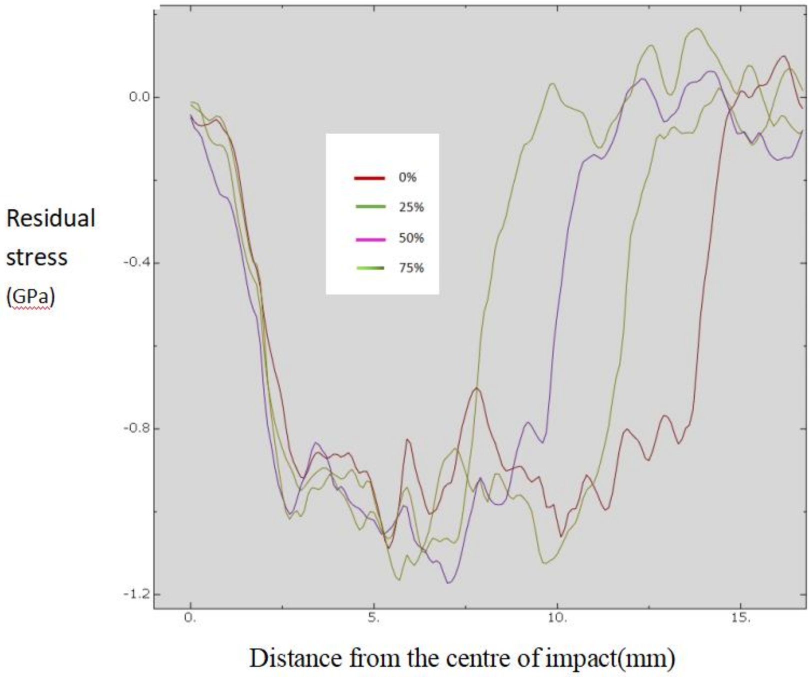

Fig. 3.8 - Residual stress distribution curves on the impact surface for different spot lap rates

3.5 Simulation of laser impact strengthening of gear tooth surfaces

In this chapter, the influence of the basic parameters on laser shockt peening has been investigated, and in this section, simulated peening of the tooth face of the gear model will be performed.The gear model used is the single tooth model of the gear created in Figure 2.4, which has a modulus m=4 and a number of teeth Z=50. Based on the results of the study of the basic parameters, the transverse mesh of the gear model is set to 100μm and the longitudinal layer depth mesh direction mesh is set to 150μm, as shown in Figure 3.9.

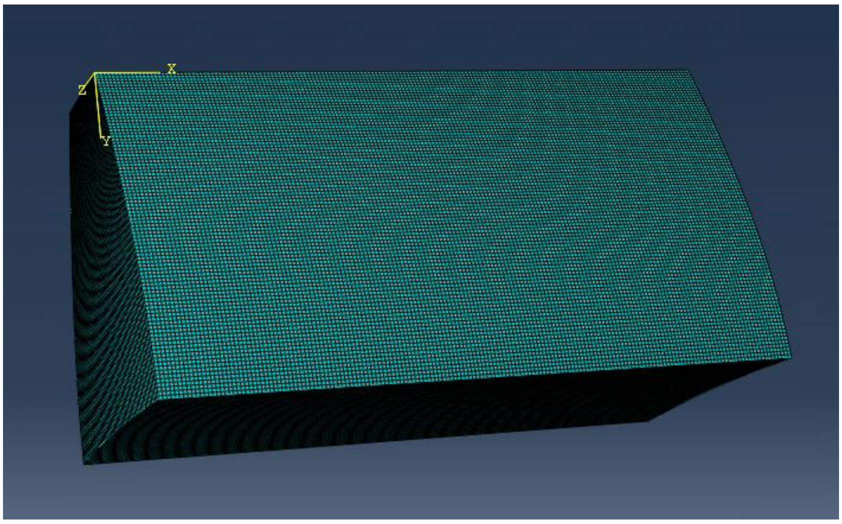

Figure 3.9 - Meshing of a single tooth model of a gear

The laser parameters for gear tooth face strengthening are: laser radius of 2mm, pulse energy of 8J, number of impacts is single, spot lap rate of 50%; this simulation is lasers shock peening of part of the tooth face area, the specific shock path is shown in Figure3.10, continuous laser impact of 12 points.

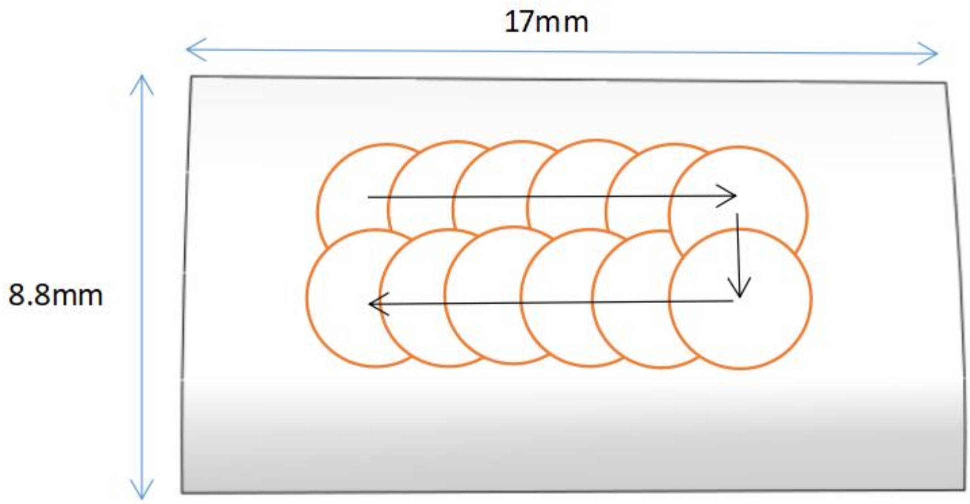

Fig. 3.10 - Schematic diagram of the laser shock peening path for gear tooth surfaces

After 12 points of continuous laser impact strengthening, a certain depth of residual compressive stress layer was formed in the area of the spot action. Figure 3.11 shows the residual stress distribution curve on the gear surface in the S_{11} direction (X-axis direction), from which it can be seen that the maximum residual compressive stress is 1.25GPa and the residual stress distribution on the gear surface is uniform. Figure 3.12 shows the residual stress distribution curve on the gear surface in the S_{22} direction (Y-axis direction), from which it can be seen that the maximum residual compressive stress is 0.78GPa and the residual stress distribution on the gear surface is uniform. From the residual stress values obtained for each point on the gear surface it can be calculated that the average residual compressive stress value in the direction of S_{11} is 634.24GPa and the average residual compressive stress value in the direction of S_{22} is 475.84GPa. As a result, laser shock peening of gear tooth surfaces creates a residual compressive stress layer at a certain depth on the gear surface, and the average residual compressive stress value along the X-direction is greater than that along the Y-direction.

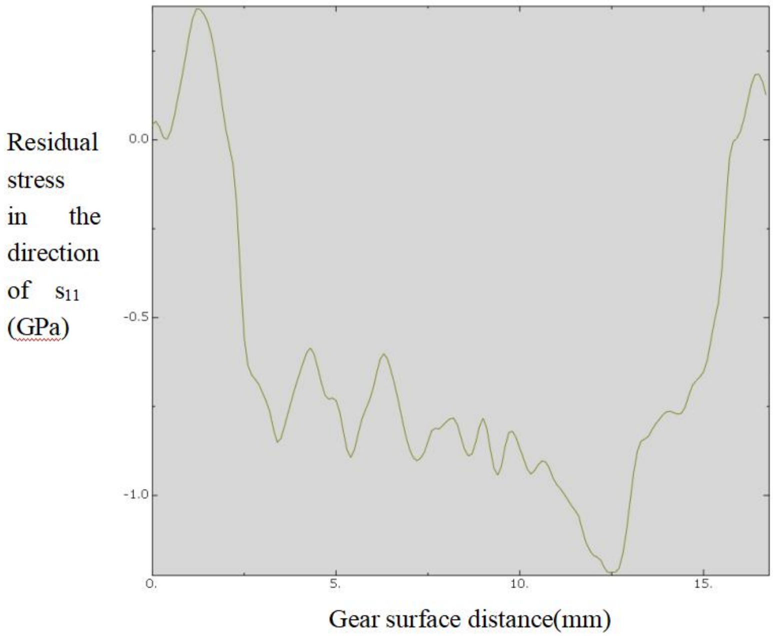

Fig.3.11 - Gear surface residual stress curve in the s_{11} direction(mm)

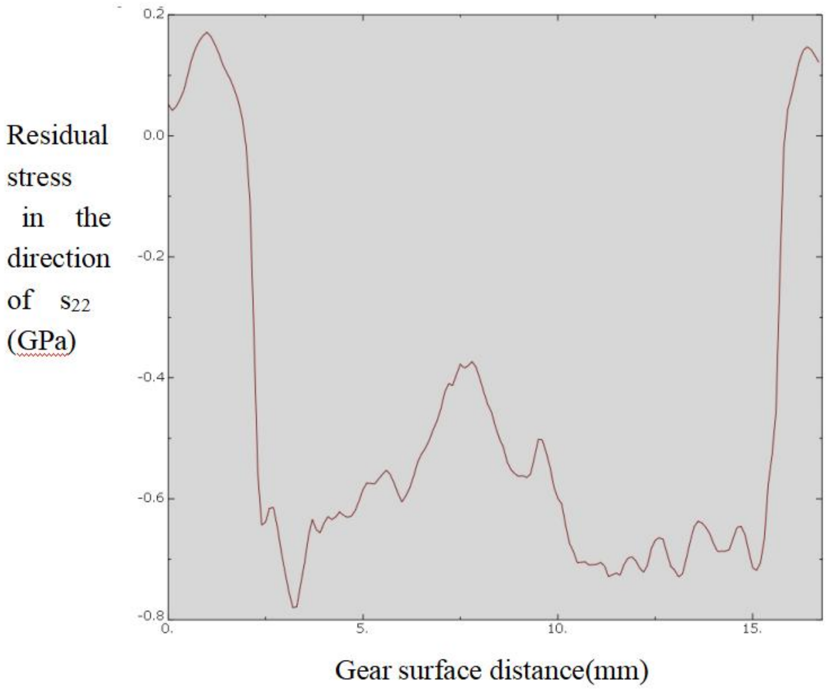

Fig.3.12 - Gear surface residual stress curve in the s_{22} direction(mm)

Conclusion to the part 3

Prior to the laser shock peening of gear tooth surfaces, this section presents a simulation of the important parameters that affect the effectiveness of laser impact peening, including laser pulse energy, spot radius, number of impacts and spot lap rate.The effect of these four parameters on the strengthening effect was successfully obtained: as the energy of the laser pulse increases, the value of the residual compressive stress and the depth of the residual compressive stress layer also increases, but too high a laser pulse energy results in the phenomenon of "residual stress voids". Increasing the spot radius can improve the strengthening effect. A small spot radius increases the laser energy density, resulting in a pressure wave much higher than the surface yield strength of the material, resulting in a sparse wave at the spot edge, which weakens the residual compressive stress on the surface. As the number of impacts increases, the strengthening effect is enhanced, but the phenomenon of "residual stress voids" also occurs at the same time, weakening the residual compressive stresses at the centre of the impact, so the number of impacts should not be increased excessively. The simulation results show that the residual stresses are not uniformly distributed when the lap rate is 0% and 25%, so the lap rate of 50% is most reasonable. Finally, laser shock peening simulations were carried out on a single tooth model of the gear. The results showed that a uniform layer of residual compressive stress was formed on the tooth surface and that the average residual compressive stress values along the X-direction were greater than those in the Y-direction.

PART 4

LABOR PROTECTION

4.1 Introduction

In order to perform laser shock peening tests on parts, a complete set of laser shock peening test equipment must be used. During the test, a voltage of 220V or more is used, and the high pressure shock wave generated by the laser can reach several Gpa or even Tpa. At the same time it has a very high strain rate, the time of action of the shock wave is only a few tens of nanoseconds, the shock wave action time is so short that the strain rate can reach 10^{-10}/s, a hundred times higher than the explosion forming, 10,000 times higher than the mechanical impact.The commonly used impact intensification techniques can reach single pulse energies of several tens of joules in the laser beam and peak powers in the Gw range.Improper handling of equipment can cause serious, even fatal, injuries to workers. There are other hazards associated with operating the equipment, such as clamping fixtures that pinch workers, laser radiation that can harm people's eyes during machining, and electrical wiring that can cause fires. In this chapter the working environment in a laser impact intensification laboratory and measures to prevent injury are considered, including how workers can protect themselves from injury.

4.2 Analysis of working conditions

The laser shock peening equipment must be in an enclosed, unoccupied space. Figure 4.1 shows the laser shock peening equipment workshop, which requires a series of programming operations on a computer outside the laboratory before conducting the test, then entering the operating room and clamping the parts to be impact peened on the equipment's workbench, after which the laboratory door is closed and the laser impacts the parts inside the laboratory. Due to the high voltage current, the high pulse laser and the mechanical clamping of the parts, possible hazards need to be considered when working.

-Be aware of leaking wires or equipment.

-High pulse laser radiation to human body

-Pinching of worker's hands by robotic arm clamps

-Noise from laser shock on workpiece.

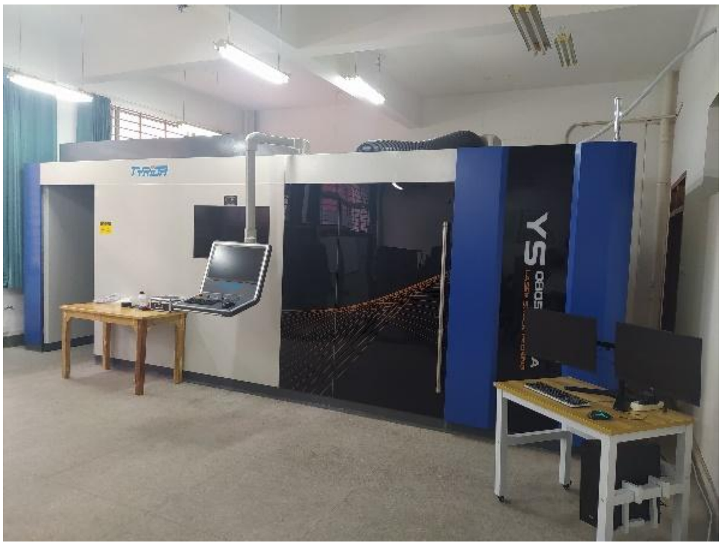

Fig. 4.1 - Laser shock peening equipment

4.3 Protection measures

Measures considered in accordance with the requirements of Q/CPBKH0095-2017 on Standards for laser use and IEC60825Edition3.0 on laser safety reporting standards.The following protective measures can be taken for the above possible hazards. Preventive measures to prevent electric shock are the following three, insulation measures: good insulation is necessary to ensure the normal operation of electrical equipment and lines, is an important measure to prevent electric shock accidents; screen protection measures: the use of screen protection devices, such as commonly used electrical insulation shell, metal mesh cover, metal shell, transformer fence, fence, etc. will be electrically charged body and the outside world to isolate to eliminate unsafe factors. Where metal materials made of screen protection device, should be properly grounded or zero; spacing measures: in order to prevent human contact or excessive proximity to the charged body, between the charged body and the ground, between the charged body and other equipment, should maintain a certain safety spacing. The size of the safety spacing depends on the voltage level, the type of equipment, the installation method and other factors.

To prevent injuries to people from laser equipment: (a) prominent signage should be installed on the laser equipment, with warnings such as "Laser Danger, Do Not Approach". (b) The internal light path system of the laser equipment should be sealed with the appropriate material as far as possible to avoid direct exposure. (c) Safety procedures should be followed, including Safe methods of collimation and adjustment of the optical path. Use of personal protective equipment: protective glasses, protective clothing.

Eye protection is mainly provided by goggles when clamping parts on the workbench. Protection against particles, fumes, molten metal particles etc. that may cause eye injury. Wear rubber gloves when operating to prevent workers from getting their hands pinched and keep the workbench floor clean to prevent workers from slipping.

4.4 Fire safety

Measures considered in accordance with the requirements of DBN A.3.2-2-2009 on fire prevention and fire protection, as well as measures in accordance with the requirements of DSTU 7113: 2009 on explosive surroundings. Fire and explosion safety is the state of an object in which the occurrence of fire and explosion is excluded, and in case of occurrence, the action of dangerous factors of fire and explosion on people is prevented.

Checking fire escape routes, fire breaks, fire-fighting equipment, fire-fighting facilities, etc. The main purpose of checking fire escape routes, fire fighting equipment, fire extinguishing equipment and fire spacing is to determine whether the fire escape routes are clear, whether the fire spacing is occupied, whether fire fighting equipment is properly equipped and in good condition, whether the fire fighting equipment is complete, whether the valves and switches of the fire fighting equipment are in the required state of opening and closing, and whether the positions of the instruments are in the normal permissible range, etc. The fire-fighting equipment is complete and effective.

Electrical equipment and wiring, plugs and sockets should be inspected regularly to keep them in good condition. An electrician must be notified for repairs if sparks, short circuits, heat and broken or ageing insulation are found that may cause such conditions. Electricity must not be overloaded.

Conclusion to the Part 4

In this section of the thesis, consider the regulatory documents for the relevant laser impact intensification equipment laboratories to understand the specific safety practices that can prevent incorrect handling resulting in worker injury.

The analysis identifies possible safety hazards in the laboratory, noting electrical wire or equipment leakage; high pulse laser radiation to the human body; mechanical arm clamps pinching workers' hands; and noise from the laser impacting the workpiece. Develop appropriate precautions to remove these safety hazards and ensure smooth work while protecting the safety of workers.

PART 5

ENVIRONMENTAL PROTCTION

With the rapid development of the global economy, aviation has also grown rapidly. As a symbol of a modern city, the airport is not only a convenient facility for providing transport, but also an engine for economic and social development. The aviation industry is a significant contributor to business operations, trade development and other sectors such as tourism and high technology. But it also causes damage to the environment, and environmental protection is an important issue that cannot be ignored in human development.

Boeing has always had a philosophy of putting the environment first. This section uses the Boeing 787 as an example. Figure 5.1 shows the Boeing 787.

Figure 5.1 - Boeing 787

Boeing's pursuit of environmental performance in its products has continued throughout the jet age. From fuel use and aircraft emissions to community noise, Boeing has made steady progress on a number of environmental factors. With the introduction of the 787 Dreamliner, Boeing has introduced the latest technology to take civil aircraft to another level of environmental performance. Boeing has always been committed to improving the environmental performance of its products because it is convinced that the right cause is the one that does not harm the environment. This is particularly true for the aircraft manufacturer, as one of the reasons people choose to fly is because they have a panoramic view of the planet's colourful natural landscape.

The Boeing 787 protects the environment in four ways：

Reduced fuel consumption：Thanks to four key technologies, the 787 Dream liner is up to 20% more fuel efficient than today's aircraft of its size. These four technologies are: new engines, increased use of lightweight composite materials, more efficient systems and advanced aerodynamics. Together, they improve the overall performance of the 787.

Reducing emissions：Carbon dioxide (CO2) is a product of fuel consumption. This means that as fuel consumption is reduced, CO2 emissions are reduced accordingly. Another key indicator of civil aircraft emissions is nitrogen oxides. Using a complex formula based on the thrust ratings of aircraft engines, specific regulations have been drawn up for the aircraft of the future but also better than future requirements. The Committee on Aviation Environmental Protection (CAEP) is working on more stringent regulations for the aircraft of the future.

Quieter take-offs and landings：Residents around airports know that the noise of aircraft taking off and landing is another important indicator of environmental performance. While Boeing is working hard to reduce fuel consumption and emissions, it is also trying to reduce the noise footprint, i.e. to reduce the range of intrusive noise pollution. The 787 Dreamliner incorporates a range of new technologies - the most important of which are acoustically treated engine intakes and serrated nacelles, the characteristic serrated edges at the rear of the engines, and other special treatments to the engines and engine cases - to ensure that all 85 decibels of noise (equivalent to that of traffic heard on the roadside) do not extend beyond the airport boundary to ensure that all the 85 decibels of noise (equivalent to the sound of noisy traffic heard on the roadside) do not extend beyond the airport boundary. In fact, the 787's noise footprint is more than 60% smaller than existing aircraft of similar size.

New production process reduces waste： The 787 is made primarily from carbon fibre composite material and because this material can be cut like fabric, the new production process creates less trim and waste. Existing aircraft are mainly made of aluminium and large pieces or chunks of material have to be crushed and then machined and used to make the aircraft structure. Typically 90% of the raw material used to manufacture aircraft components becomes scrap during the production process. While these materials can be recycled, it is certainly better to avoid wastage where possible, and the 787 composite solution addresses this efficiency issue. In addition, the design team is reducing or eliminating the use of materials that compromise the environmental performance of the aircraft and are harmful to workers' health, as required. Ultimately, new production and maintenance procedures will reduce waste and reduce the use of harmful chemicals and agents.

In designing the latest model, Boeing did not forget its long-standing commitment to improving the environmental performance of its aircraft and its unique lifecycle approach. It is by incorporating these factors that Boeing has created this ultra-efficient civil aircraft. 787 has become the most successful aircraft launch in civil aviation history thanks to its outstanding environmental performance. Airlines around the world have chosen the 787 because they share Boeing's commitment to the environment. And for passengers, they will be able to choose a more comfortable and environmentally friendly aircraft from 2008 onwards.

Conclusion to the part 5

The aviation industry, especially civil aviation, has become an important part of human environmental protection, and the noise nuisance, energy consumption and air pollution caused by such a large scale of practice should be given sufficient attention in the medium. It is gratifying to note that in the face of these problems, the aviation industry has begun to adopt positive technical measures and policies and regulations to explore the way for the sustainable development of the aviation industry and contribute to the sustainable development of mankind.

GENERAL CONCLUSION

Laser shock peening technology is one of the advanced surface peening methods in the world today and has great potential for development.In this paper, the application of laser impact peening to aircraft engine gears is investigated in a simulation simulation theory. The laser parameters suitable for the material 18Cr2Ni4WA were studied and laser shock peening simulations were carried out on an aircraft engine gear model, and good strengthening results were obtained.

The first part introduces the background and significance of research into laser shock peening technology, which has been successfully applied to the practical production and maintenance of aircraft in the USA in the late last century. More and more countries are now focusing on the technology and applying it to a wider range of applications.

The second part is to lay the foundation for the laser impact strengthening simulation by solving some basic pre-simulation problems:

-Analyse the properties of the material and select the J-C intrinsic model as the intrinsic model of the target material;

-Establishing the laser shock pressure model and solving for the maximum pressure wave.

-Determine the solution time for the dynamic analysis step during the simulation.

In the third section, four parameters affecting laser shock peening are first investigated: laser pulse energy， spot radius, number of impacts and spot lap rate. The effect of these four parameters on the laser shock peening effect is investigated and reasonable parameter values are selected. Finally, a simulation of tooth surface impact peening was carried out on a single tooth model of a gear. It was found that after laser shock peening, a certain depth of residual compressive stress layer was generated on the gear tooth surface, and the average residual compressive stress value on the tooth surface reached 634.24GPa in the X direction and 475.84GPa in the Y direction, and the residual compressive stress value in the X direction was greater than that in the Y direction.

In the fourth section, possible safety hazards are listed with regard to the working environment in the laser shock peening technology laboratory and appropriate protective measures are proposed for these hazards. The laser shock peening process has to be worked in an enclosed and unoccupied space,The wiring in the laboratory should be serviced regularly to prevent injury to workers from electrical leakage.

In the fifth part, the impact of the rapid development of the aviation industry on the environment is described, and environmental protection is an important issue that cannot be ignored in human development.The Boeing 787 is used as an example of how this aircraft is environmentally friendly. Calls on other airlines to develop better environmentally friendly aircraft.

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