Abstract

Different laser surface hardening techniques, such as laser alloying and laser solution strengthening were adopted to perform modification treatment on the local region of inset edge for 2Cr13 and 17-4PH steam turbine blades to prolong the life of the blades. The microstructures, microhardness and anti-cavitation properties were investigated on the blades after laser treatment. The hardening mechanism and technique adaptability were researched. Large scale installation practices confirmed that the laser surface modification techniques are safe and reliable, which can improve the properties of blades greatly with advantages of high automation, high quality, little distortion and simple procedure.

PACS: 81.70.-q; 42.62.-b

Keywords: Steam turbine blade; laser hardening; microstructure; anti-cavitation; application

1. Introduction

Industrial steam turbines, as key power equipment, play increasingly important roles in many areas such as the petroleum, chemical industry, light industry and other important departments of the economy. The blade is one of the key components of a steam turbine and is essential for safety operation. The role of the blade is to change the energy of high-speed gas to mechanical energy. Especially as to the last stage blades [1], the steam condenses into water droplets easily in the high-speed operation, and then small water droplets are thrown to the end of blades and burst with the high-speed centrifugal motion. Fatigue cracks will form at the end of blades after long-term running [2]. The statistic data shows that a number of accidents of turbine-generator units were caused by the failure of the blades. According to the U.S. Electric Power Research Institute (EPRI) statistical reports [3], the direct economic losses of national power plant shutdown were about 15.5-18.4 million dollars from 1977 to 1981. Especially in
recent years, due to the impact of peaking running and load downing, the bad conditions of steam turbine working exacerbated the occurrence and development of cavitation erosion. Therefore, the cavitation resistance of the blades is responsible for the efficiency and safety of turbines.

To enhance the performance of cavitation resistance and life of the blades, two kinds of important materials were used to manufacture blades [4], one of which is martensitic hardening stainless steel, and another is precipitation hardening stainless steel and precipitation hardening stainless steel. Usually, the martensitic hardening stainless steel blade (1Cr13, 2Cr13, 2Cr13MoV, etc.) is strengthened by flame quenching, induction hardening, electroplating, spraying and other methods [5], while the precipitation hardening stainless steel blade (such as 17-4PH) is embedded with Stellite alloy to enhance properties. However, the above methods can not overcome the main problems, such as deformation, cracks and the falling off of the alloyed layer. Laser processing technology can instantly generate high energy on the surface of blades to harden the substrate, which results in some unique characteristics: metallurgical bonding between the hardening material and the substrate, little heat affected zone, low deformation and high automation. Therefore, laser processing is expected to avoid the shortcomings of traditional methods completely and to be used widely.

Laser alloying and laser solution strengthening were adopted to perform modification treatment on the surfaces of 2Cr13 and 17-4PH steam turbine blades respectively in this paper, and the microstructure and properties of laser hardened layer were investigated, the applications of different laser surface hardening techniques were introduced as well.

2. Experimental procedures

2Cr13 stainless steel and 17-4PH precipitation hardening stainless steel were used as the substrates of samples. Quenching and tempering are the final heat treatment methods of the substrates. Their chemical compositions are listed in Table 1. Before laser hardening, pretreatment for the surface of samples was necessary. The surface was cleaned by sonication in acetone or alcohol. After the surface of the sample was clean and dry, the alloying powder mixed with some binder was smeared on the surface of 2Cr13 stainless steel sample. Table 2 shows the chemical composition of the alloy powder. The coating to enhance the laser absorptivity was brushed on the surface of 17-4PH stainless steel. The laser hardening experiments were carried out by a 7kW continuous wave CO₂ laser system with a CNC controlled working table. Laser beam was focused by two special integral lenses to get two kinds of beams during the two laser hardening processes. The laser alloying parameters were chosen with laser power of 1.5~2kW, scanning speed of 300~600mm/min, laser beam size of 9x2 mm², while that of the laser solution strengthening was chosen with laser power of 1~2kW, scanning speed of 200~500mm/min, laser beam size of 16x10mm². Ar was used as a melt pool shielding gas.

Table 1. Chemical composition of the substrates (wt.%)

| Substrate | C   | Cr | Ni | Cu | Mn | Si | Nb | Fe       |
|-----------|-----|----|----|----|----|----|----|----------|
| 2Cr13     | 0.16~0.21 | 12~14 | - | - | ≤0.80 | ≤0.60 | - | Balance |
| 17-4PH    | 0.04 | 4.5 | 3.3 | 0.7 | - | 0.3 | Balance |

Table 2. Chemical composition of alloying powder (wt.%)

|                  | Si | Cr  | Ni | Fe  | W   | Co  |
|------------------|----|-----|----|-----|-----|-----|
|                  | 1.3 | 2.86 | 3.29 | 0.98 | 40.24 | 51.33 |

Transverse sections of the laser hardened samples were cut, mechanically polished and etched by FeCl₃ for microstructural characterization by using optical microscopy and field emission scanning electron microscopy (SEM, Hitachi S-4700). Phase identification of the sample surface was performed by X-ray diffraction (XRD, ThermoarT-SCINTAGX’TRAX). Microhardness of hardened layer was measured on a HXD-1000 hardness tester under a load of 200g with a dwelling time of 15 s. To investigate the cavitation resistance of the laser hardened layer, an ultrasonic wave shock cavitation instrument was set up, which includes the ultrasonic wave generator, energy conversion device and a taper amplitude pole on energy conversion device, as shown in Fig.1. The surface of the sample was abraded by metallographical abrasive polish and polished by a buffing machine, then cleaned for 10
3. Laser alloying of 2Cr13 turbine blade

3.1. Microstructure and microhardness of alloyed layer

A thin alloyed layer can form on a local region of the substrate surface through laser alloying, which results in the improvement of properties of materials [6,7]. The alloyed elements were mixed with molten substrate to obtain the required depth and chemical composition under high-energy laser irradiation in a very short period of time.

The microstructure of the 2Cr13 substrate is shown in Fig.2 (a), including ferrite and sorbite composed of granular carbide. Fig.2 (b) shows the morphology of the treated layer after the laser alloying process, and Fig.2 (c) is the SEM image of alloyed layer. It can be seen that a dense alloyed layer with fine grains was generated. During the rapid heating and cooling process of laser alloying, the growth of austenite is restrained, forming a high degree refined microstructures, which is one reason for the hardness rising. The alloyed layer and the substrate are metallurgical bonded without cracks and porosity. With irradiation of the high energy laser beam, a molten pool is formed on the surface of the substrate. The added alloying powders (mainly W, Cr, etc.) are melted into the molten pool in a short time and carbonization occurs. Fig.3 shows the XRD result of the surface of laser treated layer, which indicates that the carbides such as WC, Cr7C3 form on the laser treated layer.

Fig.4 shows the micro-hardness distribution of the laser alloyed layer. The highest microhardness is 785 HV0.2, while average microhardness is 701 HV0.2, which is 1.8 times higher than that of the substrate. The thickness of the hardened layer is around 0.4mm and the hardness decreases gradually from the alloyed layer to the substrate.

Firstly, the reason for the enhancement of hardness can be attributed to formation of the carbides such as WC, Cr7C3 which have high hardness. On the other hand, the element Ni which was used to expand the region of
austenite can prevent the formation of second-phase particles and, meanwhile, improve the corrosion resistance of the alloyed layer. During the rapid solidifying process, there haven’t enough time for austenite transition, which leads to the formation of retained austenite on the surface. So the alloyed layer not only has higher hardness, but also remains high plastic toughness. Co is one kind of non-carbide forming element and becomes solid solution in austenite and ferrite. So the existing of Co can harden the substrate not only at room temperature but also at high temperature. On the other hand, when other carbide forming elements dissolve into retained austenite, Co can restrict the precipitation of carbides and forbid the gathering of precipitation phases.

3.2. Cavitation resistance of the alloyed layer

The mechanism of cavitation has not been identified by a uniform knowledge until now. The main viewpoint is that the cavitation is the high frequency blast wave caused by the collapsing cavity, which is equivalent to numerous atmospheric pressures acting on the material surface. Under continuous alternating stress, the surface of material is mechanically damaged, which results in the fatigue flake.

The 2Cr13 blade samples before laser treated and after laser alloying were immerged in the experimental set-up of the cavitation erosion as showed in Fig.1. The results of weight loss vs. time are shown in Fig.5. The weight loss
Fig. 6. The surface SEM images after cavitation erosion (a) the 2Cr13 substrate sample; (b) the laser alloyed sample

of the substrate is significantly higher than that of the alloyed sample, which shows that the material after laser alloying has higher cavitation resistance at the same conditions.

Fig.6 shows the SEM images of the cavitation erosion surfaces. For the substrate sample, deep and nubby erosion holes are uniformly distributed in the surface. No crack on the erosion surface is found, but some micro-cracks are observed at the junction of the erosion area and no erosion area. For the laser alloying sample, the erosion holes are relatively shallow at the same erosion experimental conditions. No crack is observed at the junction of the erosion area and no erosion area, which is different from the substrate sample. The variation is mainly due to the effect of rapid heating and cooling of the laser beam. In the laser alloyed layer, the grains are refined and a large number of carbide hard phases form. The diffused carbide hardened phases restrict the expansion of cracks, the flaking of surface metal and then reduce the erosion rate, which results in the cavitation resistance one time than that of the substrate.

4. Laser solution strengthening of 17-4PH blade

4.1. Microstructure and hardness of hardened layer

Usually, the precipitation hardened stainless steels (such as 0Cr17Ni4Cu4Nb(17-4PH), X5CrNiCuNb(16-4)) are performed by solution and aging treatment through placing the whole component into the furnace, which are prone to the flaws such as deformation and overheating of materials. Because of selected heating and controllable heat input of laser processing, laser beam was used to as the heat source of solution treatment for 17-4PH precipitation hardened stainless steel blade sample in this paper to fulfill the solid solution process. The solid solubility elements in the substrate diffuse during the laser process and then precipitate in the following aging. Finally, solid solution strengthening can be achieved to increase overall properties.

Fig.7 is the macroscopic image of the head part on a 17-4PH blade after laser solution strengthening. There are three different colour areas which are named as the hardened area, the heat affected zone and the substrate. The hardened width of the blade is about 28mm. Fig. 8 shows the microhardness distribution of the blade after laser solution strengthening. It can be seen that the hardness gradually reduces from 478 HV0.2 on the surface to 301 HV0.2 in the substrate, and the distribution is quite uniform. The depth of the hardened layer is about 1.8mm.

Fig. 7. The macroscopic image of 17-4PH blade after laser solution strengthening

Fig. 8. The microhardness distribution of the blade after laser solution strengthening
During the laser heating process, the supersaturated solid solutions exist as martensite and ferrite. Through heat insulation treatment for a long time, the solid solutions precipitate in certain forms and disperse in the substrate. Fig. 9 and Fig. 10 show precipitated phases in a ferritic and martensitic matrix respectively. A large number of precipitate in the ferritic matrix can be mainly found in grain boundaries and their brim, with diameter varying from 100nm to 1000nm. But only a few precipitates in the martensitic substrate are detected, with diameter of about 100nm. According to a large number of reports and analysis of the energy dispersion spectrum of martensite, the precipitation phases can be speculated to be precipitation phase $\varepsilon$-Cu (FCC) from the 17-4PH substrate.

![precipitated phase](image1)

**Fig. 8.** The precipitated phase of ferrite

![precipitated phase](image2)

**Fig. 9.** The precipitated phase of martensite

### 4.2. Cavitation resistance analysis of hardened layer

The cavitation resistance of the surface after laser treatment improves above one time than that of substrate, as shown in Fig. 10. The SEM images of cavitation erosion surfaces of the 17-4PH samples before and after laser solution strengthening at the same condition are showed in Fig. 11. The results indicate that the erosion holes on the 17-4PH substrate are clear and there are micro-cracks. However, the erosion holes of the laser hardened layer are reticular distributed, the depth of the holes are relatively shallow, and no crack is found in the overall surface. Because of the unbalanced rapid solidification process of the laser solution strengthening, the surface is featured with high hardness and strength and has refined grains. More boundaries between grains can be achieved, which may contribute to buffer the stress. So the fatigue crack cannot extend, and breaking off of grains is prevented, then the toughness and plastic property are improved, which leads to excellent cavitation resistance.

![cavitation resistance curves](image3)

**Fig. 10.** The cavitation resistance curves of the substrate and laser solution strengthened sample
5. Application

Since 2001, the research and industrial application of laser hardening on steam turbine blades has been carried out in the author’s group. At present, the laser alloying technology of turbine blades has been widely used in several steam turbine factories. More than 100,000 blades of 110 type have been laser alloyed and installed. After the detection test, the percent of pass was 100%. The blades have no distortion and their quality and safety are improved remarkably. According to the users’ feedback, the life of the blades enhances more than one time. After the laser alloying process, the risk of deformation and fracture easily caused by hardening stress during traditional quenching process such as the electroplating, flame hardening, induction hardening are reduced, so this technology can completely replace the traditional methods with high energy-consuming and pollution.

The technique of laser solid solution strengthening on 17-4PH blade was developed and had been successfully used in last stage blades installed in the 1000 MW Ultra Super Critical Steam Turbine Unit. The special production line of laser treatment for this kind of blades had been established, and the localization of manufacturing for the Ultra Super Critical Steam Turbine Unit was realized.

6. Conclusions

(1) The laser alloyed layer is significantly different from the substrate with refined grains by adding alloying elements. The uniformly dispersed hard phases form on the surface of the substrate. Compared with the substrate, the microhardness is improved about 1.8 times after laser alloying. The cavitation resistance of the laser alloyed layer increases more than one time. Therefore, due to high efficiency and low price, laser alloying is promising in improving cavitation resistance and long-term life of blades.

(2) Laser rapid solid solution strengthening can be used to precipitation harden stainless steel. The thickness of the laser hardened layer is over 1.8 mm. The highest microhardness is 480 HV and gradually descends from the surface to the interior. After laser treating, the cavitation resistance of the surface is improved one time than that of the substrate. A large number of grain boundaries of FCC structure of ε-Cu are the main reason for dispersion and solid solution strengthening.

(3) The laser hardening techniques show unique characteristics. Practice has proved that laser hardening technology is more safe and reliable than traditional techniques and can improve performance of turbine blades.

Acknowledgements

The authors would like to appreciate financial support from National Science Foundation of China (50971117).
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