Effect of Ultrasonic Surface Rolling Process on Solid Particles Erosion Performance of Ti-6Al-4V

Yuqing Shi*, Yixin Liua, Xiao Lib and Yong Zhangc

Key Laboratory of Pressure Systems and Safety, Ministry of Education, School of Mechanical and Power Engineering, East China University of Science and Technology, Shanghai 200237, P.R. China

*Corresponding author e-mail: syq1214@gmail.com, ayxliu@mail.ecust.edu.cn, bceustlx@163.com, cecustzy@139.com

Abstract. In this paper, the effect of ultrasonic surface rolling processing (USRP) on the solid particles erosion (SPE) performance of Ti-6Al-4V was studied. USRP is one kind of material surface treatment processing technology that combines deep rolling processing and ultrasonic vibration, which induces deep levels of compressive residual stresses and nano-crystalline layer with a gradient structure. The material was processed at an annealing temperature of 760°C. During the SPE, three angles of impact at 30°, 60°, and 90° are contemplated with an approximate flow capacity of 7±1 kg/h and a maximum exposure time of 100min per specimen, taking measurements of weight intervals around every 5min to determine the mass loss. The wear mechanisms at small angles were mainly: plastic deformation and displacement of material. While at higher impact angles, the mechanisms were mainly: cutting, pitting, fractures, and cracks. After the USRP, the erosion resistance ability of Ti-6Al-4V is increased by 2~3 times than before, and the influence is more obvious under low impact angle. Transmission electron microscope (TEM) and scanning electron microscope (SEM) are used to characterize the microstructure and morphology of the alloy. Cumulative mass loss was utilized to quantify the characterize the erosion resistance.

1. Introduction

In industrial application, wind turbines, pipe fittings, hearts casting, pipelines carrying liquids or gases always operate in harsh environment of steam with high velocity and sand of different shapes for very long time, which will lead to the occurrence of erosion wear on the components and have great impact on the safe and stable operation as well as the energy output of the equipment [1]. This occurs due to the synergy of the impacting tiny sands mixed with steam and rotation blades, which usually termed as “solid particles erosion (SPE)” [2]. SPE is a progressive loss of the material from a solid surface due to accumulative impacts by the particles. Therefore, studying the erosion behavior of the turbine blades is of great necessity.

SPE is a complex phenomenon due to many interacting parameters such as impacting speed, impact angle, accumulated impact time and the condition of target material where we studied annealed Ti-6Al-4V and SiC particles with the diameter of 20 ~ 50µm in this experiment [3]. The strength, toughness and hardness as well as the micro structure of the target material are all influential factors determining its
erosion resistance [4]. SPE consist of several stages: incubation period where mass loss is negligible, acceleration stage where mass loss is significant; maximum erosion rate stage where mass loss is at the terminal steady state with erosion rate remaining constant. The acceleration stage is the focus point of this study since this is the most evident and primary status during the damage of material, where erosion rate at this stage is characterized as the erosion resistance of the material [5].

In order to prolong the life time of the components. There is a method of mitigating SPE that can be classified into two distinct categories with certain conditions: (1) active methods which basically minimize the main factors causing the erosion such as reducing the volume of tiny particles; (2) passive methods which aim at enhancing the surface and mechanical properties of Ti-6Al-4V materials [6]. Passive methods has been adopted due to its economic feasibility. Ultrasonic surface rolling process (USRP) is a relatively new and promising technology to induce a nano crystallized surface with a nano gradient layer in the surface of the alloy and increase the resistance of materials to surface-related failures, such as fatigue and stress corrosion cracking [6]. The main reason for the improvement of fatigue strength and other mechanical properties comes from the effect of ultrasonic vibration to impact the target material, relieving tensile residual stress, improving micro hardness and introducing high compressive residual stresses into surface layers of materials[7] [8].

In this work, the effect of USRP on the SPE performance of Ti-6Al-4V was investigated. Much attention was given to the influence of impact angle on the SPE performance. With the USRP of specific parameters, the alloy was processed and characterized by methods like TEM and SEM. Analysis of eroded material suggests the erosion phenomenon and points the way to enhance the materials for better properties during the service performance.

2. experimental

2.1. Annealing process

For the present study, Ti-6Al-4V alloy rods, purchased from BAOTI Group was investigated. Samples were prepared by wire cut with the thickness of 5 mm. Annealing treatment was conducted to obtain excellent α + β duplex structure. The annealing procedures are: heat the samples in the furnace to 960°C for 250 mins from room temperature(around 20°C), and maintain the temperature for 160 mins, then take the samples outside the furnace for air cooling.

2.2. Properties test

The metallographic microstructure of target material was characterized by an optical microscope (OM) (showed in Fig 1) and scanning electron microscope (SEM). Moreover, the chemical composition profile within the transition zone was analyzed by a SEM equipped with Energy Dispersive X-ray Spectroscopy (EDS), showed in Table 1.

HXD-1000TMC/LCD micro Vickers hardness tester was used through the static indentation method to measure the hardness variation of the Ti-6Al-4V alloy in the depth direction before and after USRP.

![Figure 1. The metallography of Ti-6Al-4V alloy.](image-url)
Energy dispersive spectrometer (EDS) was used to test the material components. And the chemical properties is showed in Table 1.

Table 1. Chemical composition (wt %) of Ti-6Al-4V alloy.

| Element | C  | Al  | V   | Ti   | Others |
|---------|----|-----|-----|------|--------|
| Content | 3.27 | 6.00 | 4.33 | others |

The mechanical property was tested in INSTRON8801 material testing machine with the loading rate of 0.6 mm/mins. The annealed Ti-6Al-4V alloy has a yield strength of 870 MPa, a tensile strength of 948 MPa, an elastic modulus of 112 GPa, and an elongation of about 18.4%. Figure 2 shows the stress-strain curve of Ti-6Al-4V alloy.

![Figure 2. The stress-strain curve of Ti-6Al-4V alloy](image)

Also, in order to characterize the evolution of microstructures and the different depths of grain morphology and grain boundary characteristics in a more detailed way, JEOL 2100 Transmission Electron Microscopy (TEM) was used to analyse microstructures of different depths.

2.3. Ultrasonic surface rolling processing

The surface of the annealed Ti-6Al-4V alloy was modified using USRP apparatus. Ultrasonic rolling process is mainly composed of three steps: (1) Sample preparation: milling the Ti-6Al-4V alloy plate on the CNC milling machine (Fig. 7) and using the grinding machine to polish the samples. (2) Select appropriate processing parameters: summarized in Table 2; (3) Fix the sample on the workbench of the CNC machining center and execute the process following the path in Fig. 3.

Table 2. Parameters of ultrasonic surface rolling process

| Static stress/N | Amplitude/μm | Frequency/kHz | Feed speed/ (mm/mins) | Head diameter/mm |
|----------------|--------------|---------------|-----------------------|-----------------|
| 720            | 20           | 20            | 3000                  | 10              |

Figure 3. Schematic illustration of USRP path
The device was used to fabricate the nano crystallized layer. A typical photograph showing the schematic pictures shows the construction of USRP equipment and the rendering graph was showed in Fig. 4. In this setup, the ultrasonic transducer converts electrical energy from the ultrasonic generator into ultrasonic vibration with a frequency of around 20 kHz. After the converted displacement signal is input into the amplitude transformer, the displacement signal is amplified by the amplitude transformer and then input to the processing head which is the shock ball, so that the processed workpiece is subjected to ultrasonic processing. Under a static pressure, the shock ball vibrates rapidly between the ultrasonic transducer and the target surface.

The impact signals and current signals generated from the ultrasonic generator (showed in Fig. 5) which has a frequency tracking function within a certain range (5 kHz).

![Figure 4. Assembly and rendering drawing of the Ultrasonic equipment](image)

![Figure 5. Ultrasonic generator device and CNC milling machine](image)

Notably, in this system design process the structure of the amplitude transformer, the main component of the ultrasonic processing system, was optimized. The new type of amplitude transformer adopts the shape of Bezier curve, and genetic algorithm method was used to optimize the shape of the curve, which could improve the working ability of the amplitude transformer: reducing the stress concentration of the amplitude transformer and increasing the vibration amplification factor under the same length. A closed-loop genetic algorithm system is established between ANSYS and MATLAB. Also, the processing head adopts a replaceable sleeve design in order to facilitate the replacement of the worn head ball, and it is also possible to adapt different processing heads in the future.

2.4. Erosion Test
SPE tests were carried out using the parameters illustrated in Table 3
Table 3. Experimental parameters used in erosion test

| Factors             | Parameters                                                                 | Explanation                                                                 |
|---------------------|---------------------------------------------------------------------------|-----------------------------------------------------------------------------|
| Steam              | -                                                                         | Steam Valve is fully open (100%);                                           |
| Impact Particles    | SiC particle with light green color and the diameter varies from 50~75 μm | Particles are sieved from raw material, corresponding to a mesh size of 200~240 mesh; |
| Powder Feeder       | Pipe pressure: 0.4 MPa; Powder feed rate: 4.1 g/min                       | Powder feed rate number is 30 on the screen and the rate is measure by experiment; |
| Pressure Balance Pipe | Pipe pressure: 0.6 MPa                                                   | Balance the pipe pressure, avoiding the stream goes into powder feeder;      |
| Impact Angle        | 30°, 60°, 90°                                                             | The erosion angle: between the erosion direction                          |
| Impact time         | 2~7 mins                                                                  | Maximum stable erosion time of the steam generator is 7 mins when the steam valve is fully open; |

3. Result and discussion

The scanned image after USRP is shown in Fig. 6(a), and it is compared with the unprocessed sample Fig. 6(b). It was obvious that the surface of the specimen became smoother and more uniform after the process.

Fig. 7 (a) to (e) show the evolution of microstructure from the material surface to the depth of 300μm, covering all states of the deformation under USRP. Fig 7(e) shows the morphology of the structure at 300μm from the surface, where the grain size of α grain is still not much different from the original grain size, maintaining the typical dual-phase structure of Ti-6Al-4V. Fig 7(d) suggests that α crystals begin to elongate and the dislocation structures emerged. The elongated grains with a size range from 1 to 3μm, further illustrates the occurring of grain refinement. Fig 7(b) illustrates the structure at the depth of 30μm, where the surface layer has become an equiaxed Nan crystalline layer, and the grain size is refined to about 20nm. The dislocation structure begins to appear continuously. The overall series of TEM photos show that Nan crystalline refinement of the surface layer has been induced by USRP in the Ti-6Al-4V alloy.
Figure 7. Cross-section TEM image of Ti-6Al-4V alloy: (a) at the top surface; (b) at 30μm from the top surface; (c) at 80μm from the surface; (d) at 150μm from the surface; (e) at 300μm from the surface;

The surface hardness of the sample after USRP was improved (Fig. 8), and the hardness decreased gradually with increasing distance from the surface. In the area of severe plastic deformation, the direct cause of the significant increase in micro-hardness is the presence of Nan crystals. However, as the depth of the surface increases, the grain size also increases, and the effect of grain refinement decreases, resulting in a significant decrease in micro-hardness.
This phenomenon is consistent with the traditional Hall-Petch relationship and the results of the research on the mechanical properties of other nano crystalline materials. Therefore, through USRP, the grain size of the surface layer refines, the grain boundary and dislocation density increase, making the surface hardness greatly improved.

Figure 8. The near surface micro-hardness profile of Ti-6Al-4V alloy processed by USRP

For the effect of the angle in SPE, it can be explained from the energy point of view that the mass loss of the material is a superposition of both the deformation wear and the cutting wear. It can be concluded from Fig.9 that at small angles of attack, e.g. 30°, the amount of deformation wear of the material is greatly reduced. Therefore, the erosion wear rate of the material at 30° is much lower than the mass loss caused by the impact deformation at large attack angle, e.g. 60°-90°.

Figure 9. Cumulative quality loss of processed (a) and un-processed (b) Ti-6Al-4V with the impact angle of 30°, 60°, 90°

Also, there is a crossover of the mass loss curves between 60° and 90°. Because in the process of vertical impact, work hardening occurs in the initial stage, which protect the surface material instead. However, as the impact time increases, large-scale fragmentation begins to appear, and caused small cracks initiation.

Comparing the effect of USRP at different angle (Fig. 9), the effect on the erosion rate at small angles is more significant. Under the 30° impact angle, it can be seen that the material has an erosion time of up to three times the same mass loss, comparing the horizontal coordinate values at the same ordinate value. The erosion performance is up to three times higher, and at 90° impact angle, the erosion resistance of the rolled material is approximately twice that of the unprocessed material. Thus, USRP
increased the erosion resistance of Ti-6Al-4V by 2 ~ 3 times.

**Figure 10.** Cumulative quality loss of processed and un-processed Ti-6Al-4V with the impact angle of 30° (a), 60° (b), 90° (c)

SEM pictures shown in Fig have six group of samples at different impact angle in two column. The surface appearance of the material before rolling is more uneven, which means that the erosion before processing is more sever. As can be seen in the comparison between Fig. 11(c) and Fig. 11(d), there are several ploughing and cutting damage in Fig. 11 (c). The most severe damage in Fig. 11 (e) presents honeycomb structure. The overall shape of the material after rolling is much finer. The reason for this is that USRP improved the anti-erosion performance, and it is more difficult to remove the particles from the target surface.
As we compare the pictures before and after processing, the following conclusions can be drawn:

1. Under the 90° angle of attack, the damage of the material is more consistent with the erosion law proposed by the extrusion forging model. The surface is mostly a pit-like structure generated by hammering, and it has obvious undulating topography features.

2. At an impact angle of 30°, the material has a more flat topography and kind of directional characteristic, similar to the scouring effect. The topography is smoother than erosion at the impact angle of 90°. It shows that under the low erosion angle, the way of the particles destroying the material is
mainly the ploughing, which belongs to the first type of cutting, leaving traces in the form of elliptical shallow pits.

(3) The impact state of the material is between 30° and 90°.

4. Conclusion and OUTlook

The conclusions obtained from this study are as follows:

(1) By selecting specific rolling processing parameters and processing routes, the Ti-6A1-4V alloy can be treated to form a gradient nano-layer with a thickness of 300 μm on the surface, and a nano-gradient of the Ti-6A1-4V alloy using a transmission electron microscope. Observations of the microstructures at different depths of the layer showed that the crystals exhibited a gradient distribution of the reinforcing layer structure and the grain size of the surface nano-crystals was less than 100 nm. The surface hardness distribution test shows that rolling increases the surface hardness of the material by about 30%.

In the process of improving the ultrasonic rolling processing device, the main purpose is to increase the static pressure load of the processing head to obtain higher processing strength and toughness of the material. Genetic algorithm was used to optimize the the outline of Bezier shape transformer. This design has greater structural amplification and less stress concentration compared with other structures.

(2) The effect of USRP under different angles of impact on the erosion properties of the material was studied through comparative tests. The wear principles basically conformed to the micro-cutting model with low erosion angle and the extrusion forging model with large angle. After the treatment, the erosion resistance of the material is improved by 2 to 3 times. And under the low impact angle, USRP has greater impact on the erosion performance.

(3) To analyze the erosion profile of the material before and after the roll treatment with different angles of attack, it can be conclude that under the 90° angle of attack, the damage pattern meets the hammering model of extrusion forging; while under the 30° angle of attack, the damage pattern is more consistent with the first type of cutting model. After processing, the shape of the material is more finely crushed, and it is more difficult to remove the target material by collision with the particles, which can be seen as a reflection of improving the erosion resistance of the material.

For further study, the USRP system as an economical processing could be further optimized, the design of the ultrasonic processing equipment is very complicated and it is difficult to coordinate various components. Also in this paper, the influence of rolling processing on Ti-6A1-4V alloy is studied, but the effect of other types of metal has not been verified, which may obtain better strength and toughness of material as well as other good results.

The model of erosion wear performance could be further investigated, since only qualitative analysis was performed. If further research is required, quantitative analysis can be performed to validate and supplement the existing erosion wear model.

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