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Discrete characteristic and edge effect during subsurface microhardness measurement of Ti-6Al-4V alloy

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Abstract

This paper investigates the discrete characteristic and edge effect of subsurface microhardness of Ti-6Al-4V alloy. The results show that the discrete degree of Ti-6Al-4V alloy microhardness decreases with increasing loading force. When the loading force is 200 gf, only five microhardness measurements are needed to reduce the interference of discrete characteristic. Importantly, the edge effect was found during measuring the subsurface microhardness of Ti-6Al-4V alloy. The edge effect means that the microhardness value is little when its indentation position is close to a workpiece edge. Finite element analysis reveals that the low support strength of workpiece edge is responsible for the edge effect. This study further clarifies that a Vickers indenter is not suitable for characterizing the machined subsurface microhardness on account of the limitations of edge effect and indenter size.

1. Introduction

Ti-6Al-4V alloys have the characteristics of high specific strength, good thermal stability, corrosion and creep resistance, which are widely used as aero-engine fans, compressor blades, compressor disks and shells \cite{1–4}. Ti-6Al-4V alloy parts work in high temperature and pressure environments. Hence, Ti-6Al-4V alloy blade often generates fatigue failure \cite{5}. It is worth noting that the fatigue crack sources are generally occurred at the location of the machined subsurface damage of Ti-6Al-4V alloys \cite{6, 7}. Therefore, the mechanical property evaluation of the machined subsurface of Ti-6Al-4V alloys attracted extensive attentions. Hardness is a common index used to evaluate material mechanical property. Because the hardness reflects the material ability to resist the elastic-plastic deformation. A high hardness value is prone to result in fracture failure \cite{8, 9}. Conversely, the ability of a material anti-fatigue failure is insufficient. Therefore, an in-depth understanding on the machined subsurface hardness of Ti-6Al-4V alloys is extremely important to assess fatigue performance \cite{10–12}.

At present, although large numbers of microhardness measurements of Ti-6Al-4V alloys have been carried out, it is difficult to compare various research conclusions because of different experiment conditions. In particular, loading force significantly affects the measured microhardness value of Ti-6Al-4V alloys. For example, the Ti-6Al-4V alloy microhardness value is 380 HV when loading force is 25 gf \cite{13}. If loading force increases to 50 gf, the measured microhardness is about from 320 HV to 315 HV \cite{14, 15}. Microhardness value is 325 HV when loading force is 100 gf \cite{16}, which is higher than that under a loading force of 50 gf. When the loading force is 200 gf, the measured microhardness values are relatively close, such as 341 HV and 340.6 HV \cite{17, 18}. Microhardness value increases to 361 HV when loading force is 500 gf \cite{19}. These studies show that the Ti-6Al-4V alloy microhardness has significant discrete phenomenon when the loading force varies from 25 gf to 500 gf. Otherwise, Moussaoui et al \cite{20} found that even though loading force is same, the difference between the maximum and minimum microhardness is large. For instance, the maximum microhardness is 402.5 HV and minimum value is 305.8 HV when loading force is 200 gf. The maximum microhardness is 378.0 HV and minimum value is 312.5 HV when loading force is 300 gf. Therefore, it is necessary to study the discrete characteristic of Ti-6Al-4V alloy microhardness to guide the selection of experimental conditions \cite{21, 22}.

The discrete characteristic of Ti-6Al-4V alloy microhardness has affected the understandings of mechanical properties on the machined subsurface \cite{23, 24}. To date, many researches reported a softening position of
microhardness on the machined subsurface of Ti-6Al-4V alloys, where the microhardness is much less than the material matrix microhardness [25–27]. Yang et al [13] found that the minimum microhardness occurred at the distance of 20 μm to a workpiece edge on the milled subsurface of Ti-6Al-4V alloy. Wang et al [14] pointed out that a softening phenomenon of microhardness was appeared at the distance of 20 μm near subsurface edge in the side-milling of Ti-6Al-4V alloy. Li et al [16] measured the microhardness of milled Ti-6Al-4V alloy in the subsurface depth from 10 μm to 90 μm under a loading force of 100 gf. They found that the minimum microhardness was 180 HV which existed at the position of 20 μm to the milled subsurface edge. Tan et al [28] also observed the softening position of microhardness at the distance of 20 μm to a workpiece edge on the end-milled subsurface. Moussaoui et al [20] reported a similar softening phenomenon of microhardness on the end-milled subsurface of Ti-6Al-4V alloy. An interesting phenomenon can be found from the above summaries that the softening position mostly occurs at the distance of 20 μm to the subsurface edge. Currently, many scholars believed that the softening phenomenon of Ti-6Al-4V alloy microhardness was related to the material microstructure changes induced by high cutting temperature, such as over-aging [29, 30], thermal softening [13, 14, 16, 28, 31] and vanadium diffusion from β-phase into surrounding α-phase [20]. However, the experimental evidences reported by these literature are inadequate to identify the formation reasons of softening phenomenon of Ti-6Al-4V alloy microhardness.

This paper proposes another hypothesis that the softening phenomenon of Ti-6Al-4V alloy microhardness correlates to indentation position. When the indentation position is very close to a workpiece edge, which will cause a lower microhardness value, i.e. edge effect. In addition, the discrete characteristic of Ti-6Al-4V alloy microhardness is not researched systematically. Consequently, this paper will investigate the discrete characteristic and edge effect of Ti-6Al-4V alloy microhardness with the aid of Vickers indentation under different loading forces.

### 2. Experimental material and methods

Ti-6Al-4V alloy base material is made by forging and its heat treatment process is shown in figure 1. The chemical compositions and mechanical properties of Ti-6Al-4V alloy are shown in tables 1 and 2. Ti-6Al-4V alloy has α and β phases, as shown in figure 2. The material microstructure is a typical basketweave structure. It can be seen from figure 2 that the light gray elongated slats are α-phase with the width of 5 –10 μm, and the dense black gaps around α-phase are β-phase.
Samples were prepared by using a wire electric discharge machine. Indentation surface was prepared by successive grinding and polishing processes. The polished surface was corroded by the way of Kroll reagent (HF : HNO₃ : H₂O = 1 : 2 : 17) and observed by using optical microscope as shown in figure 2.

A Vickers indenter was used in this study to compare with other reported results. The square-pyramidal-diamond Vickers indenter has an angle \( \theta \) of 136° between opposite sides. Indentation diagonal lengths \( d_1 \) and \( d_2 \) were measured after indenting with a loading force \( P \), and then their average value \( d \) was taken. Vickers microhardness is calculated as following [32, 33].

\[
H = \frac{2P}{d^2} \sin \frac{\theta}{2} = 1.8544 \frac{P}{d^2}
\]

Loading forces were selected as 50 gf, 100 gf, 200 gf and 300 gf, and holding time was 15 s. Figure 3 shows an example of indentation positions during measuring subsurface microhardness under a loading force of 50 gf. The distances from indentation to edge were different among various loading forces.

3. Results and discussion

3.1. Effect of loading force on the discrete characteristic of microhardness

Five sets of indent experiments were conducted on each sample for individual loading force, as shown in figure 4. It can be seen that indentation area raises in proportion to loading force. This means that larger indentation area covers more \( \alpha \)-phase and \( \beta \)-phase. Twenty microhardness values were measured under each loading force, as shown in figure 5. It can be found that although loading force is same, the twenty microhardness values are different. The fluctuation of microhardness value under a loading force of 50 gf is the most serious. These results indicate that the measured microhardness of Ti-6Al-4V alloy has an obvious discrete characteristic. Therefore, if the numbers of measured microhardness is insufficient, it is difficult to obtain the accurate average microhardness value of Ti-6Al-4V alloy.

To investigate the discrete characteristics of Ti-6Al-4V alloy microhardness, the maximum and minimum microhardness values under each loading force were analyzed, as shown in figure 6. The difference between the maximum and minimum microhardness is 57.3 HV under a loading force of 50 gf. When a loading force is 100 gf, the difference decreases to 37.3 HV. Interestingly, the differences are 24.2 HV and 27.6 HV under loading forces of 200 gf and 300 gf, respectively. In this case, the differences are similar although loading forces are increased. It can be inferred that the discrete characteristic of Ti-6Al-4V alloy microhardness is related to loading force.

The standard deviation of twenty microhardness values under each loading force was calculated. In this way, the discrete characteristic of Ti-6Al-4V alloy microhardness can be further analyzed quantitatively. The larger
standard deviation, the higher discrete degree \[^{34}\]. Standard deviation is calculated as following.

\[
\sigma = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (x_i - \mu)^2}
\]  

(2)

where \(\sigma\) is a standard deviation, \(N\) is a total number of samples, \(x_i\) is a datum, and \(\mu\) is a mean value.

It can be found from figure 7 that the discrete degree of measured microhardness values is the highest under a loading force of 50 gf. When the loading force increases to 100 gf, the standard deviation is 9.82. Specially, when the loading force increases from 200 gf to 300 gf, the corresponding standard deviations are 6.68 and 6.48, respectively. This shows that the discrete degree of measured microhardness decreases with the increase of loading force. But when the loading force exceeds 200 gf, its influence is very faint.

The influence of loading force on the microhardness discrete characteristic is related to the microstructure type and distribution of Ti-6Al-4V alloy. The microhardness of \(\beta\)-phase is higher than that of \(\alpha\)-phase in Ti-6Al-

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**Figure 3.** Schematic diagram of subsurface indentation positions.

**Figure 4.** Indentation morphology.
Figure 5. Measured microhardness under different loading forces.

Figure 6. Maximum and minimum microhardness values.

Figure 7. Standard deviation of measured microhardness values.
4V alloy [20, 35], which means that the ratio of \( \alpha \)-phase and \( \beta \)-phase significantly affects the measured microhardness. As can be seen from figure 4 that the indentation diagonal length is only 16 ± 0.5 \( \mu m \) when a loading force is 50 gf. Such small indentation size is close to the size of \( \alpha \)-phase or \( \beta \)-phase. As a result, the discrete degree of the measured microhardness values under a loading force of 50 gf is the highest due to the different percentage of \( \alpha \)-phase and \( \beta \)-phase. When loading forces are 200 gf and 300 gf, their corresponding indentation areas are large enough to cover more \( \alpha \)-phase and \( \beta \)-phase. In this case, the difference of material microstructure beneath indentation is insignificant.

Because the Ti-6Al-4V alloy microhardness has obvious discrete characteristic, it is important to find a suitable evaluation index of the discrete characteristic for scientific research and practical application. Consequently, average microhardness value was investigated on four samples. Five microhardness values were measured under each loading force on a single sample to calculate individual average value. Total average value was obtained from twenty microhardness measurements. It can be seen from figure 8 that the smaller the loading force, the greater the difference of average microhardness among four samples. For example, when a loading force is 50 gf, the average microhardness value of a single sample significantly differs from the total average microhardness value. This means that it is inaccurate to obtain the actual microhardness value of Ti-6Al-4V alloy by measuring only five data under a small loading force due to discrete characteristic. However, when a loading force is 200 gf, the average microhardness value of a single sample is close to the total average microhardness value. This means that the Ti-6Al-4V average microhardness can be obtained by only measuring five indentations under a loading force of 200 gf. Otherwise, figure 8 shows that the difference of total average microhardness is in the range from 1.0 HV to 6.8 HV among different loading forces. This study implies that it is necessary to conduct a preliminary experiment to choose an appropriate loading force before measuring the microhardness of multiphase materials such as titanium alloys.

### 3.2. Effect of indentation position on subsurface microhardness

Ten indentation experiments were conducted to calculate average microhardness value at each distance near sample subsurface edge. It can be seen from figure 9 that indentation shape is not a standard square and two diagonal lengths are not same when indentation position is close to the sample subsurface edge. Figure 10 shows average microhardness values at different indentation positions. It can be seen from figure 10 that microhardness is smaller and smaller when indentation position is close to subsurface edge. For example, microhardness value is only 310.8 HV when the distance from indentation to edge is 20 \( \mu m \) under a loading force of 200 gf. The microhardness value of 310.8 HV is much lower than the microhardness values of 334.3 HV and 354.4 HV corresponding to the distances of 60 \( \mu m \) and 100 \( \mu m \), respectively. This shows that edge effect appears when measuring the subsurface microhardness of Ti-6Al-4V alloy. In other word, the smaller the distance from indentation to edge, the lower the measured microhardness value.

To explore the formation mechanism of edge effect, finite element analysis was carried out by using ABAQUS software. It can be seen from figure 11 that the finite element model size is 300 \( \mu m \times 300 \mu m \times 50 \mu m \). The workpiece mesh is 8 nodes linear hexahedral element C3D8R. The indenter was set as a rigid body with the mesh of 10 nodes quadratic tetrahedral element C3D10. The boundary conditions are shown in figure 12.
workpiece bottom is completely fixed. The indenter only retains the freedom of Z direction. The material properties are shown in table 2.

Figure 13 shows the finite element simulation results of microhardness indentation of Ti-6Al-4V alloy under a loading force of 200 gf. It can be seen from figure 13 that indentation depth and diagonal length are the largest when the distance $l$ from indentation to edge is 20 $\mu$m, which corresponds to the smallest microhardness value of 299 HV. This is because the support strength of material edge is weak, which causes indentation shape change.
As shown in figure 13(a), material edge produces bulge deformation, which leads to the increase of a vertical diagonal length. As a result, the corresponding microhardness value is decreased according to the equation (1). To avoid the edge effect of microhardness, the choice of indentation position is critical. It can be found from figures 13(b) and (c) that corresponding microhardness values are 328 HV and 349 HV with the distances of 60 μm and 100 μm, respectively. When the distance is 100 μm, its corresponding microhardness is close to the total average microhardness. Hence, the distance from indentation to edge should be at least three times larger than the indentation diagonal length to measure accurate microhardness value [33].

To date, many researches reported that a minimum microhardness value often appears at the distance of about 20 μm from indentation to edge [13, 14, 16, 21, 22]. Although researchers thought that this phenomenon was caused by cutting heat, there were not sufficient evidences to support this explanation. To clarify this confusion, the finite element simulation of indentation at the distance of 20 μm was further carried out under different loading forces. It can be seen from figures 14(a) and (b) that the bulge deformations of material edge were occurred under the loading forces of 200 gf and 100 gf. Their corresponding microhardness values are 299 HV and 306 HV, respectively, which are much lower than the average microhardness value of Ti-6Al-4V alloy shown in figure 8. However, the material edge did not generate bulge deformation when a loading force was 50 gf. Its corresponding microhardness value is 313 HV. This suggests that edge effect is the primary reason which causes the minimum microhardness at the distance of 20 μm from indentation to edge. A similar machining softening phenomenon was investigated near the subsurface edge of AISI 52100 steel through Knoop and nanoindentation experiments by Warren et al [36]. They also believed that edge effect caused low hardness at the indentation position of workpiece edge. This clarification is useful to guide the selections of indentation position and loading force during measuring microhardness on machined subsurface.

Vickers indentation was widely used to evaluate the variation law between microhardness and machined subsurface damage depth. And then the subsurface damage depth can be determined by distinguishing the difference between subsurface and matrix microhardness value. However, it can be known from the above analysis that the edge effect of subsurface microhardness measurement inevitably affects the critical value. Even though a loading force is 50 gf, its indentation diagonal length is about 17 μm. In this case, the distance from indentation to edge should be at least 51 μm to avoid edge effect. But the machined subsurface damage depth of Ti-6Al-4V alloy is generally about 50 ~ 60 μm [1, 10, 17, 19, 37, 38], which is close to the given distance of

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**Figure 12.** The boundary conditions of indentation finite element model.

**Figure 13.** Finite element simulation of indentation at different distance (a) $l = 20 \, \mu m$, (b) $l = 60 \, \mu m$ and (c) $l = 100 \, \mu m$. 

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The machined subsurface microhardness can not be characterized accurately with the aid of Vickers indenter due to the limitation of edge effect. By comparing different indenter shapes, it is reasonable to characterize machined subsurface microhardness by using a Knoop indentation.

4. Conclusions

This paper studies the discrete characteristic and edge effect of Ti-6Al-4V alloy microhardness with the aids of Vickers indentation experiments and finite element analysis. Conclusions are as following:

First, the discrete degree of Ti-6Al-4V alloy microhardness decreases with increasing loading force, which is related to the proportion of α-phase and β-phase beneath indentation. The discrete characteristic is the minimum when using a loading force of 200 gf. In this case, only five microhardness measurements were required to obtain the average microhardness of Ti-6Al-4V alloy. The difference between the maximum and minimum microhardness is in the range from 1.0 HV to 6.8 HV when a loading force changes from 50 gf to 300 gf.

Second, edge effect was found during measuring the machined subsurface microhardness of Ti-6Al-4V alloy, i.e. the measured microhardness value is small when indentation position is close to a sample edge. To avoid the edge effect of microhardness measurement, the distance from indentation to edge should be three times greater than the indentation diagonal length under corresponding loading force. Vickers indentation is not suitable to characterize the subsurface microhardness of machined Ti-6Al-4V alloy because of the limitation of edge effect.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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