Enhancing Precision and Reducing Surface Damage in Ti-6Al-4V ELI Cortical Screws through Optimized Polishing Techniques

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***Abstract*—The components of implants used in the human body must possess precise dimensions, strength, load resistance, and corrosion resistance. Titanium alloys, particularly Ti-6Al-4V ELI, are favored for implant components because of their excellent biocompatibility and corrosion resistance. Precision is crucial because inaccuracies in size can affect the performance of implants. This research aims to reduce surface damage on titanium alloy cortical screw threads by using polishing techniques. The study used Ti-6Al-4V ELI, and polishing was conducted at spindle speeds of 1000, 1200, and 1400 rpm for durations of 90, 100, and 110 min with materials such as Porang powder, silica sand, and abrasive dust. Dimensional accuracy was assessed using a profile projector, and surface texture and damage were evaluated through SEM. Results showed that polishing significantly reduced surface damage, thereby producing a smooth surface. The error in thread peak dimensions was reduced to 1.2%, which remains to be within the acceptable range of less than 2%. Long polishing times removed a large amount of material, thereby enhancing surface quality. These findings suggest that polishing using abrasive materials can improve the surface quality of cortical screws. Future research should explore optimizing polishing parameters for varied implant materials and configurations to enhance clinical outcomes.**

***Index Terms*—polishing, threads, errors, damage**

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I. Introduction

In biomedical engineering, the functionality and success of implant components, particularly cortical screws, rely heavily on their dimensional accuracy and surface integrity. Cortical screws are essential for facilitating the union of fractured bones during orthopedic procedures; thus, their precision is critical [1]. Dimensional inaccuracies can lead to improper fit and instability, which compromise the mechanical performance and can delay the healing process. Furthermore, surface damage, such as increased wear and tear or diminished corrosion resistance, can introduce localized stress concentrations, potentially weakening the screw over time. Addressing these challenges is crucial for improving the longevity and reliability of biomedical implants.

Titanium alloy materials, such as Ti-6Al-4V ELI, are widely used in medical applications because of their superior properties, including a high strength-to-weight ratio, resistance to high temperatures, excellent fracture toughness, and outstanding corrosion resistance [2]–[4]. These characteristics ensure good adaptability within the human body and minimize the risk of foreign body reactions and side effects [5], [6]. Despite these advantages, achieving the necessary precision and surface quality during manufacturing proves challenging. Existing processes often leave residual surface imperfections [7]; thus, effective postproduction treatments are necessary to enhance surface properties.

High precision in implant components is indispensable for ensuring their effective placement in the body without adverse effects. This finding is particularly true for components such as cortical screw threads, where even slight deviations can impact their performance when interacting with matrix threads [8]. Polishing processes can significantly influence surface roughness and enhance the surface smoothness of implant components [9]. Tsui et al. found that the particle size of the polishing medium is critical, with small particle sizes yielding smooth surfaces; similarly, high spindle rotation speeds contributed effectively to surface refinement [10].

Research, including works by Uppal et al. and Heran et al., highlights the importance of polishing in improving surface roughness and mechanical accuracy, particularly for complex workpiece surfaces such as threaded bolts [9], [11]. Additionally, studies by Ibrahim et al. underscore that using high cutting speed parameters and adjusting cutting depth can optimize thread surface quality, crucially impacting frictional interactions during implantation [6], [12].

The objective of this research is to develop a systematic approach to polishing Ti-6Al-4V ELI cortical screws by focusing on reducing surface damage and enhancing dimensional precision through various factors, such as rotational speed, powder type, and polishing time. This novel approach is intended to provide a high safety factor during the surgical insertion of screws into fractured bones, thereby advancing the practical applications in biomedical engineering and improving patient outcomes. This study aims to contribute significantly to the development of reliable and durable implant components by optimizing the parameters mentioned, thereby extending their service life in clinical settings.

II. Method

The material or workpiece used in this research is the Ti-6Al-4V ELI cortical screw with an HA 4.5 thread type according to ISO 5835 standards manufactured through a turning process, as illustrated in Figure 1. Moreover, the polishing is conducted using a polishing machine, namely, the KRISBOW 16 mm drill machine (Figure 2). The workpiece is clamped in the machine holder and placed in a container where polishing occurs. Polishing is conducted for a specific duration, after which the workpiece is removed for dimension measurement and surface damage assessment.

The threaded bolt dimensions are measured twice—before and after polishing. Dimension measurements are performed using a profile projector by placing the workpiece in front of the projector. The thread dimensions are read on the layer by activating and positioning the workpiece correctly (Figure 3). The surface damage occurring on the polished threaded bolts is assessed using the SEM-EDX Zeiss EVO MA 10 (Figure 4). The process involves preparing the workpiece sample and placing it inside the chamber to observe surface profiles and types of damage.

The polishing process is conducted using a polishing machine, where the spindle speed factors include 1000, 1200, and 1400 rpm and polishing durations of 90, 100, and 110 min. The types of powder used are Porang powder, silica sand, and abrasive dust. The spindle speed of the drill machine is controlled by the machine, whereas the polishing time is determined using a stopwatch. Porang powder, silica sand, and abrasive dust are standardized in mesh size through a sieving process with 100 mesh before use.

TABLE 1
COMBINATION OF POLISHING PARAMETERS

No.	Rotational speed (rpm)	Time (min)	Polished materials
1	1000	90	Porang
2	1000	100	Silica sand
3	1000	110	Husk ash
4	1200	90	Silica sand
5	1200	100	Husk ash
6	1200	110	Porang
7	1400	90	Husk ash
8	1400	100	Porang
9	1400	110	Silica sand

The measurement of cortical thread dimensions includes minor diameter, primary diameter, thread height, peak-to-peak distance, α angle, and β angle. The measurements are taken three times to obtain average values. Table 1 details the design of the polishing parameter combinations. The combination of smoothing parameters is designed using an Orthogonal Array design L9, as shown in Table 1.

III. Results and Discussion

A. Screw Comparison Between Before and After Polishing

Figures 5 and 6 show a comparison of the surface condition of Ti-6Al-4V ELI cortical threads before and after polishing. On the surface of the unpolished thread, the remnants are sticking precisely at the thread peaks. However, only a small portion of the thread peaks experience this. In theory, one of the causes of the chips adhering to the thread peaks is the cutting temperature. The high temperature during cutting causes the chip material to phase change from solid to semisolid, thereby forming a bond between the thread surface and the chip. Such bonding only occurs at high cutting temperatures [2]. Therefore, the cutting temperature is controlled by selecting cutting parameters and conditions to prevent material adhesion.

From a visual observation, another form of surface damage on the threads is the presence of small chips scattered on the thread surface, particularly in the valleys. These chips do not adhere firmly but cannot be easily removed by blowing air. The abundance of such chips on the thread surface leads to errors in thread dimension measurements. These tiny chips on the thread surface are caused by the scattered chip fragments, where the surface conditions are hot. As a result, these tiny chips stick when they fall on the surface but not firmly. Although these chip grains are small, their large quantity can impact dimension measurement results, although not significantly.

Figure 6 shows the cortical threaded bolts polished at different polishing times. The polishing results indicate an improvement in surface smoothness; in particular, the threaded bolt surface appears uniform and smooth. No apparent difference can be observed between the three bolts, but in theory, the longer the polishing is performed, the more material is released from the surface [13]. This finding indicates that the threaded bolt surface becomes increasingly smooth. However, the deviation from the original size becomes increasingly significant as the amount of material released from the workpiece surface increases. Therefore, obtaining the right polishing time becomes crucial because the goal is to obtain threaded bolts with the correct size and a smooth surface. This outcome can facilitate the insertion of threaded bolts to connect fractured bones during surgery.

B. Dimension Errors of Screw Pitch

Import Figures 7, 8, and 9 show the error level in the peak-to-peak distance of the threaded bolts after polishing. The errors after polishing have a significant difference from those before polishing. The error level after polishing is greater than that before polishing.

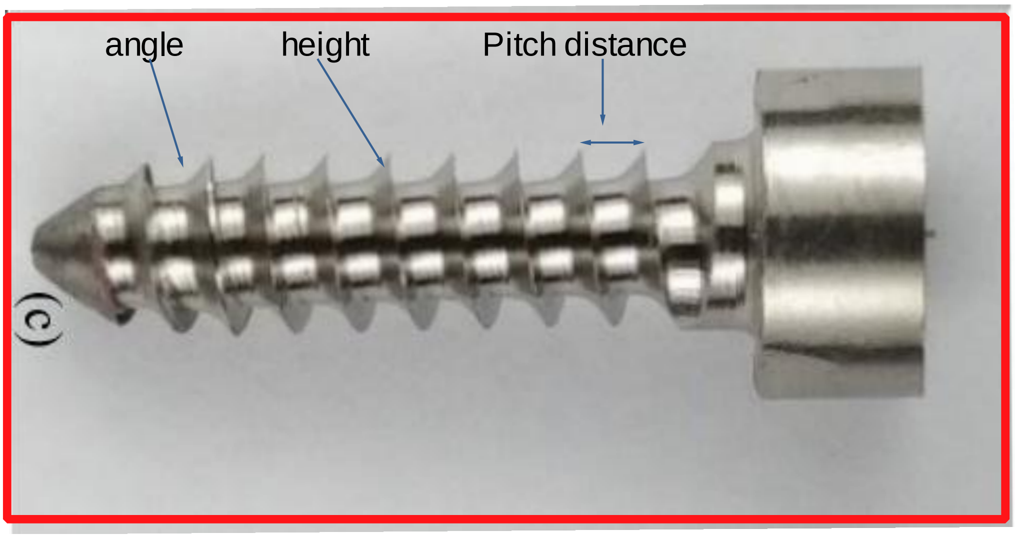

Fig. 1. Cortical threaded bolt (Ti-6Al-4V ELI)

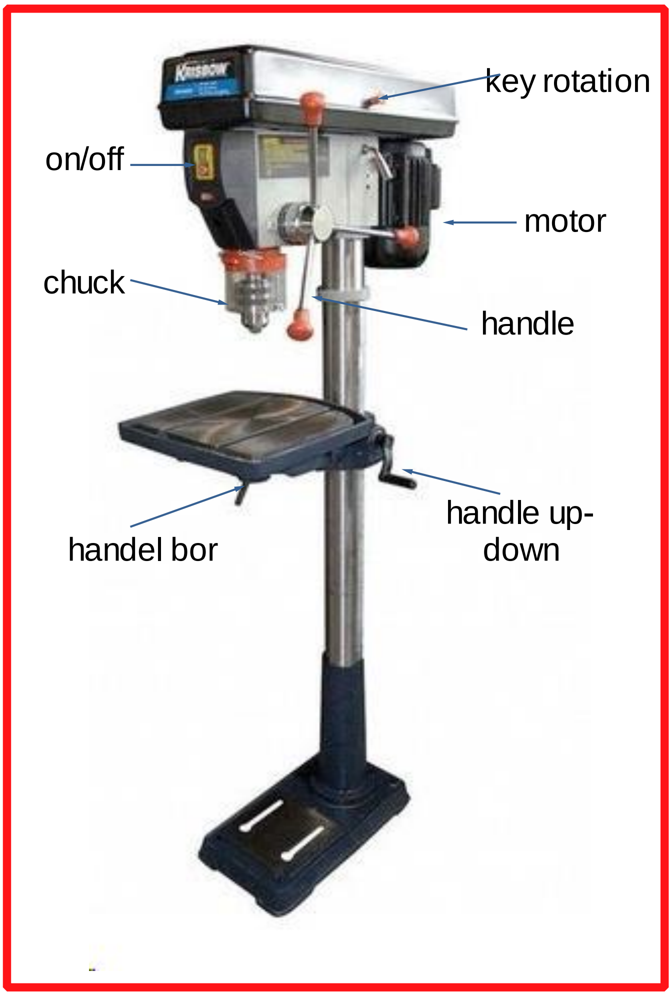

Fig. 2. KRISBOW 16 mm drilling machine

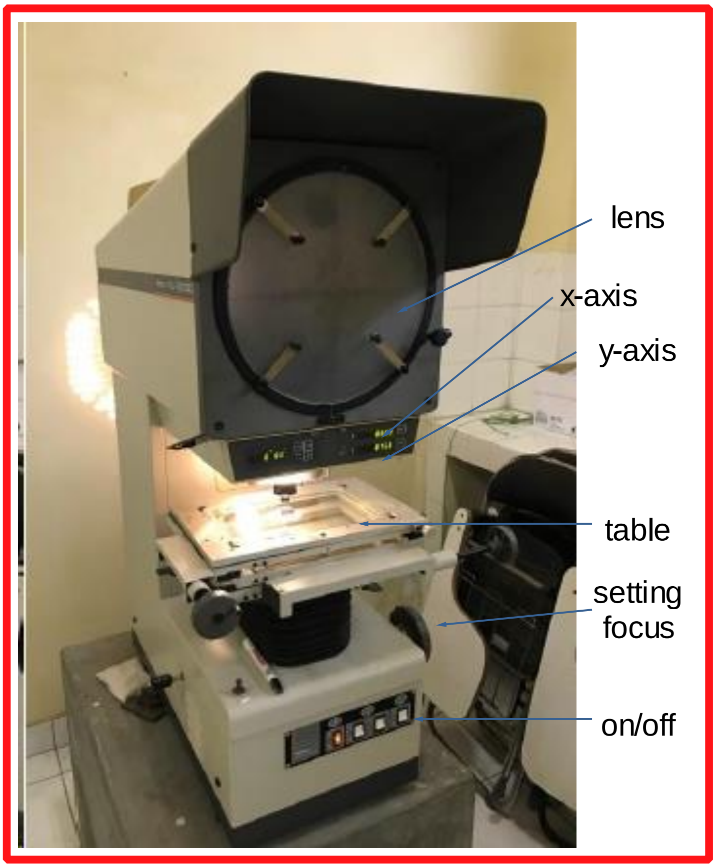

Fig. 3. Profile projector used in this experiment

Fig. 4. SEM-EDX Zeiss EVO MA 10 for identifying dimension errors

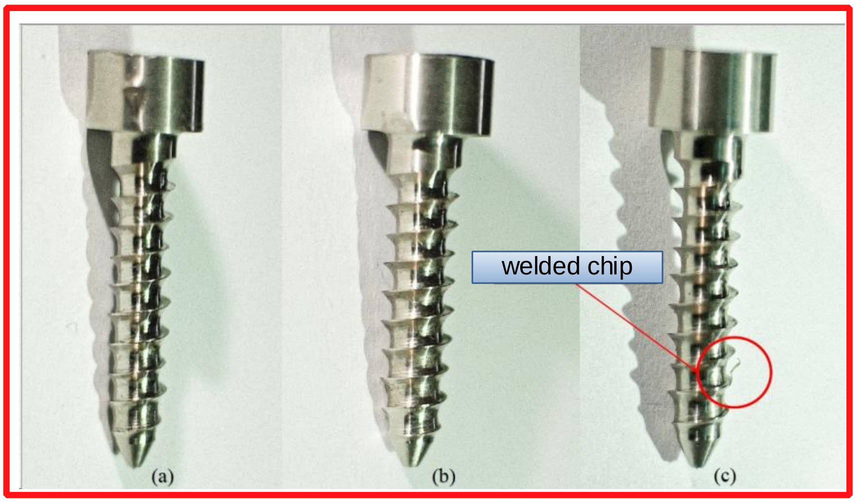

Fig. 5. Threaded screw cortical before the polishing process

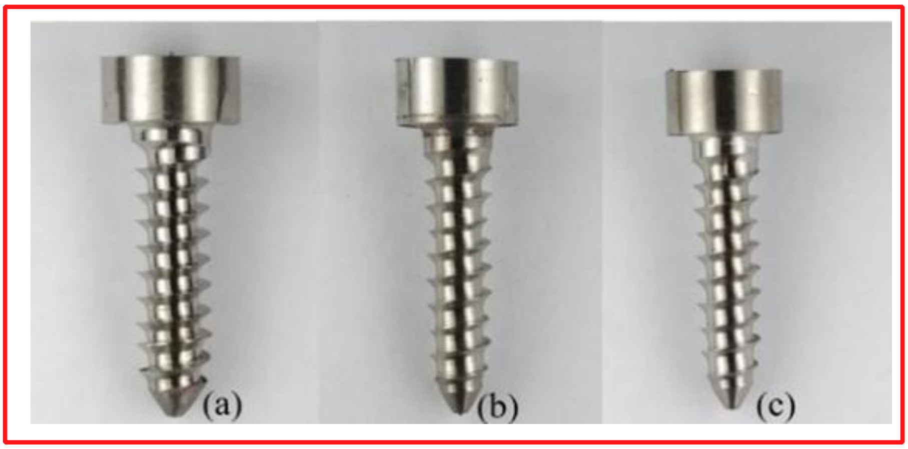

Fig. 6. Polished screw for (a) 90 min, (b) 100 min, and (c) 110 min.

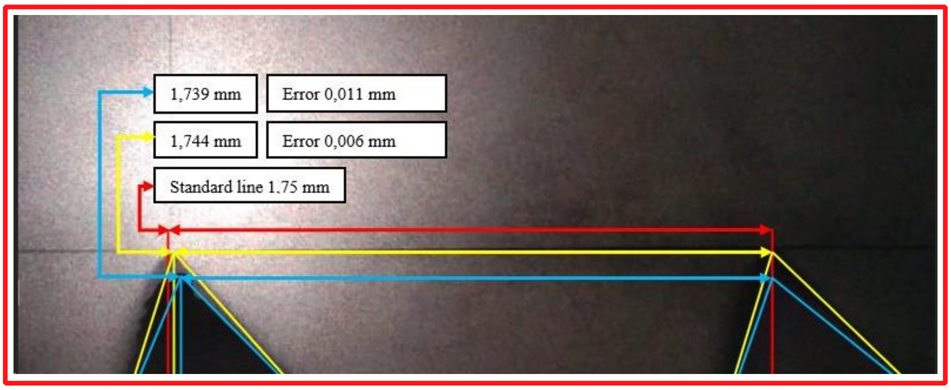

Fig. 7. Comparison of pitch peak distance errors before and after polishing at 90 min.

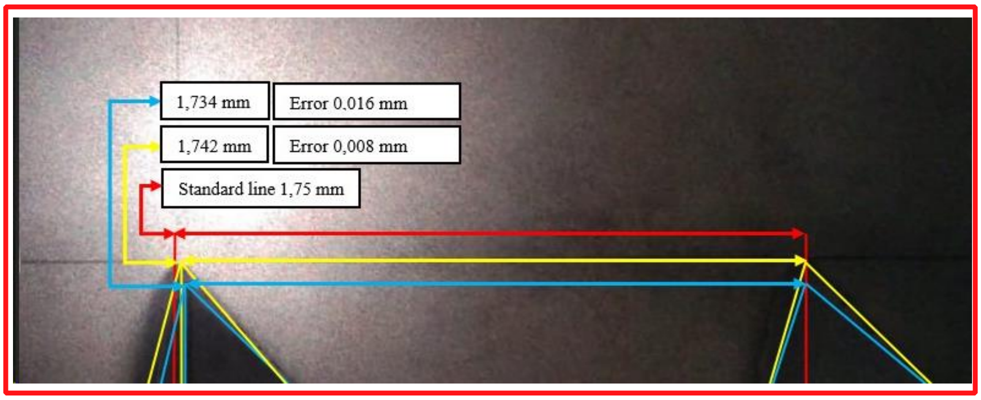

Fig. 8. Comparison of pitch peak distance errors before and after polishing at 100 min.

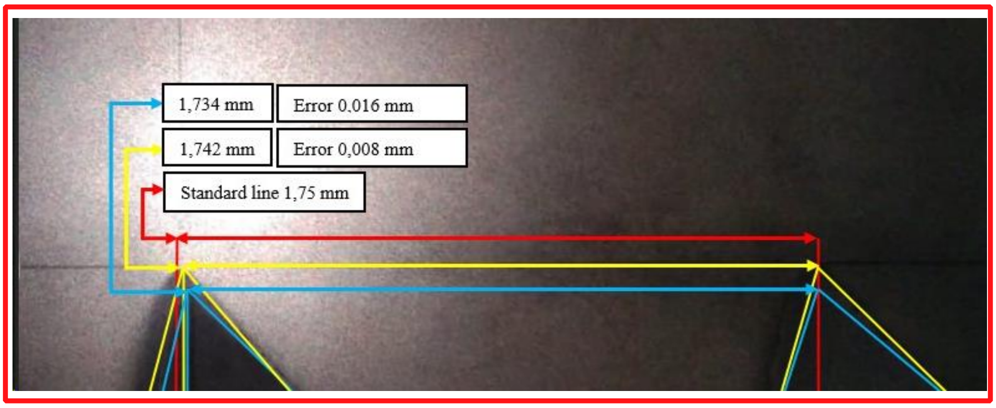

Fig. 9. Comparison of pitch peak distance errors before and after polishing at 110 min.

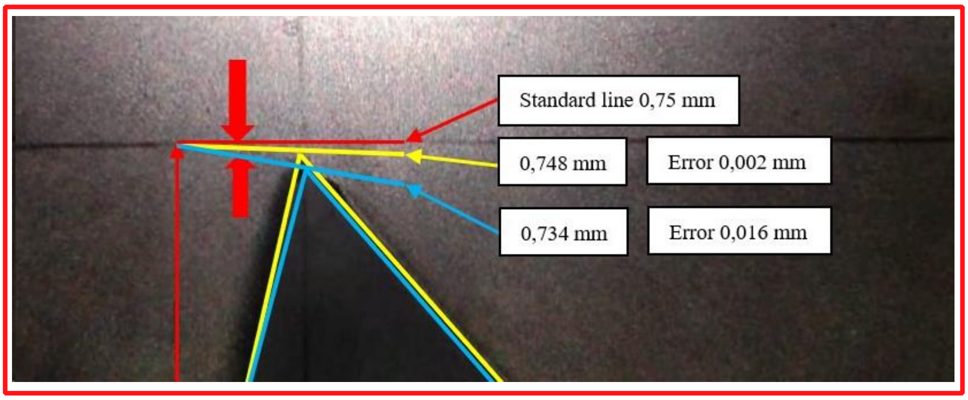

Fig. 10. Comparison of thread height errors before and after polishing at 90 min.

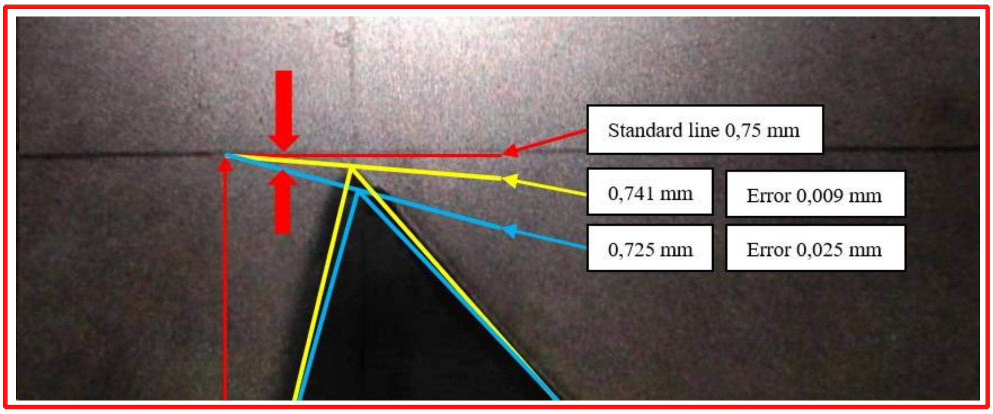

Fig. 11. Comparison of thread height errors before and after polishing at 100 min

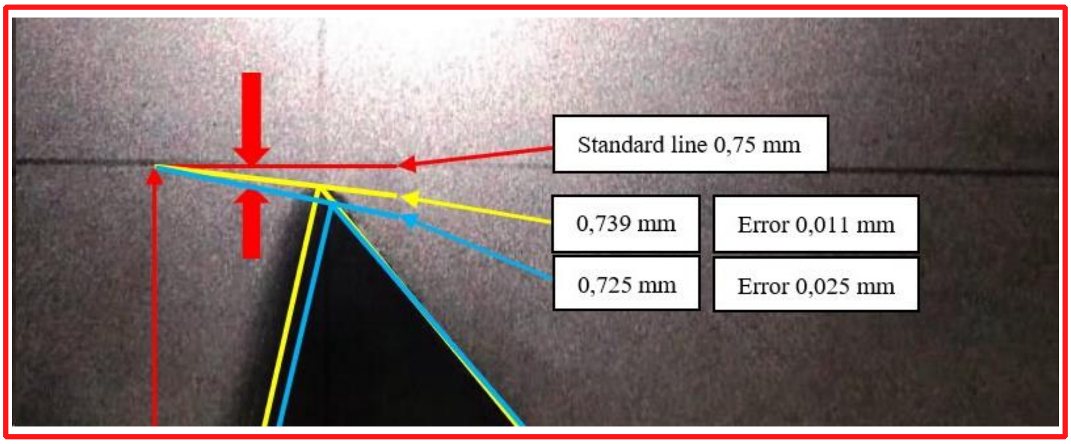

Fig. 12. Comparison of thread height errors before and after polishing at 110 min.

The magnitude of the peak-to-peak distance error difference between before and after polishing is approximately 50%. Figure 7 shows that the dimensional error before and after polishing is 0.006 mm (yellow line) and 0.011 mm (blue line), respectively. In general, the longer the polishing process is, the higher the amount of the removed threaded material is. However, the resulting surface is improved. Dimensional accuracy and surface smoothness are two important factors; however, surface smoothness facilitates the process of inserting bolts without causing damage to the fractured bone [6].

The magnitudes of the errors in the peak-to-peak distance of the threaded bolts after polishing are 0.62% (polishing time: 90 min), 0.91% (polishing time: 100 min), and 1.2% (polishing time: 110 min). These values are small because they are all less than 2%. An increase in the error percentage can be observed with the increase in polishing time. However, the highest error rate is 1.2%, occurring during a polishing time of 110 min; this result is still acceptable as the error is less than 2% [12].

C. *Dimension Errors of Screw Height*

The errors in the peak-to-peak distance of the threaded bolts after polishing are 0.62% (polishing time: 90 min), 0.91% (polishing time: 100 min), and 1.2% (polishing time: 110 min). These error values are considered negligible because they are all below 2%. The error percentage increases with a long polishing time. However, the highest error rate is 1.2%, occurring during a polishing time of 110 min; this result is still deemed acceptable as the error remains below 2% [12].

During the 90 min polishing time, the error in thread height increases to 0.016 mm, indicating an increase of 0.014 mm. Although this increase is relatively significant compared with the overall thread height, the height error is only 1.8%. The same trend is observed during the 100 and 110 min polishing times, with thread height errors being 2.0% and 1.8%, respectively. The errors are considered acceptable because the magnitude of errors is still below 2%. Therefore, the polishing process within a specific time (maximum of 110 min) can improve surface smoothness and reduce surface damage. This scenario provides advantages such as facilitating the insertion of threaded bolts and reducing the risk of bone damage during surgery. A smooth threaded surface should ease bolt insertion into the bone and reduce the risk of bone damage [1]. However, if the insertion of threaded bolts leads to bone damage, then it is undesirable.

D. *Dimension Errors of Screw Alpha Angle*

Figures 13, 14, and 15 show the measurement results of the cortical thread alpha angle under polishing times of 90, 100, and 110 min, respectively. The error in the cortical thread alpha angle before polishing is 0.05°, and it increases to approximately 3.5° after polishing. The increase in the alpha angle error by 3.45°, whether for polishing times of 90, 100, or 110 min, is considered an acceptable error. Compared with the alpha angle (35°), the error rate is 1%, which is deemed acceptable [4]. Despite the increase in the alpha angle error, the smoothness of the threaded bolt surface significantly improves. The increased surface smoothness and reduction in surface defects facilitate the insertion of threaded bolts during surgery [1]. Similarly, the ease of bolt insertion with reduced torque can reduce the risk of bone damage during bolt insertion.

In general, the reduction in the surface of the threaded bolt occurs more significantly at the thread's peak than at the bottom of the thread. This phenomenon can be observed in Figure 13, where the blue line is significantly below the red line. Figure 13 shows a substantial reduction in the material at the thread's peak. In theory, the tangential velocity at the thread's peak is greater than the tangential velocity at the thread's base. Therefore, reducing the peak height and increasing the angle inclination facilitate bolt insertion. The required torque is low because the threaded bolt's peak surface area in contact with the bone is small (shallow).

E. *Dimension Errors of Screw Beta Angle*

Figures 16, 17, and 18 display the error in the cortical thread beta angle measured using a profile projector, with measurements taken at polishing times of 90, 100, and 110 min, respectively. The cortical thread beta angle generally increases after polishing. The average increase in the error of the beta thread angle is 7.16°. Compared with the standard angle of 3°, the error in the beta angle is quite significant. Therefore, a large error is unacceptable because it alters the shape of the cortical thread profile. This substantial change in the cortical thread beta angle is caused by numerous alterations at the thread's peak. Moving at a high tangential velocity, the sharp-shaped peak results in significant surface abrasion. Thus, polishing must be performed within a relatively short time to achieve a minor error in the beta angle.

F. Dimension Errors of Screw Beta Angle

The surface texture damage on Ti-6Al-4V ELI cortical threaded bolts created using a lathe machine includes abrasion, chips, broken thread peaks, adhered material, and serrated thread peaks, as shown in Figure 19. The dominant types of damage are chips on the threaded surface and serrated thread peaks. Abrasive damage is caused by polishing particles' excessive grinding of the threaded surface [4]. Another possibility is that during polishing, the temperature increases, thereby causing polishing particles to adhere to the surface rather than quickly move away. Some particles have adhesive properties, leading to tearing effects on the surface. Nevertheless, the abrasion on the cortical threaded bolt surface is caused by the polishing particles' grinding.

Surface damage in the form of fractures at the thread peaks is likely caused by cutting forces during polishing. The thin thread peak thickness makes it prone to fractures and is influenced by the polishing temperature. The polishing temperature in the thread peak area is higher than that in other areas because of the high tangential polishing speed [11]. However, the portion of thread peaks experiencing fractures is minimal. Thus, this phenomenon is likely caused by interactions with powder particles in a heated state, thereby leading to material attraction in the direction of the workpiece rotation. A similar scenario applies to serrated thread peaks caused by a pushing force in the direction of the rotation on the thin thread peak area. The pushing force in the direction of the workpiece rotation causes some materials on the thread peaks to shift, thereby resulting in intermittent breaks resembling serrations.

The type of surface damage observed under SEM examination consists of small chips scattered across most of the threaded surface at the thread peaks and valleys. These tiny chips are only loosely attached and do not form strong bonds. They are caused by tiny particles or detached material adhering to the surface. Nevertheless, this outcome does not significantly affect the dimensional measurements of the threads and only slightly impacts surface smoothness.

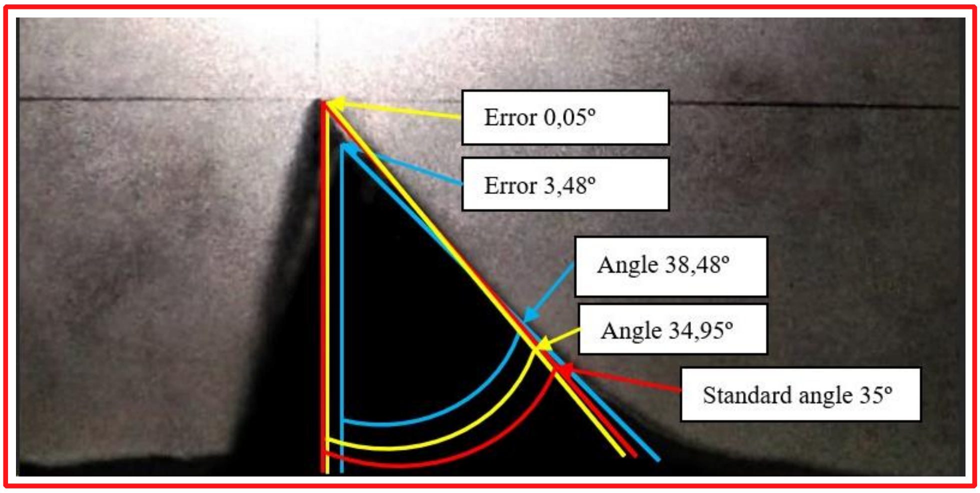

Fig. 13. Comparison of thread angle α errors before and after polishing at 90 min.

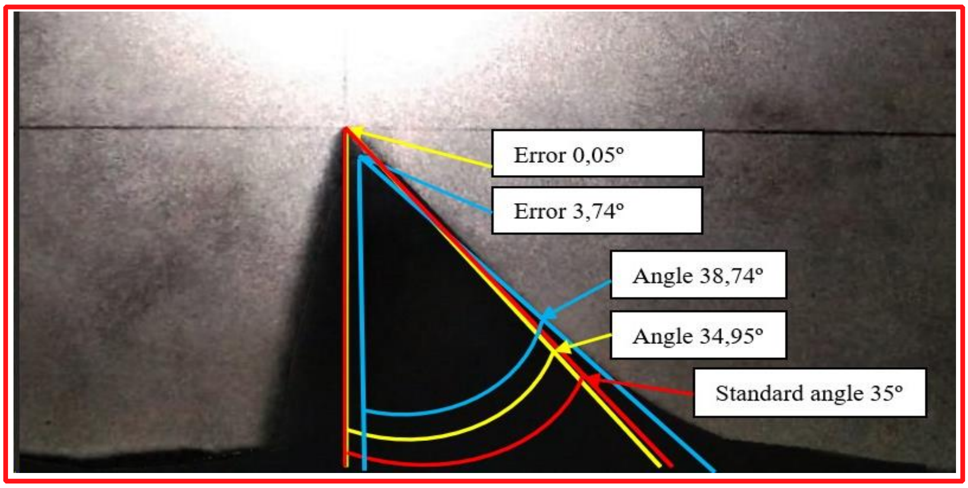

Fig. 14. Comparison of thread angle α errors before and after polishing at 100 min.

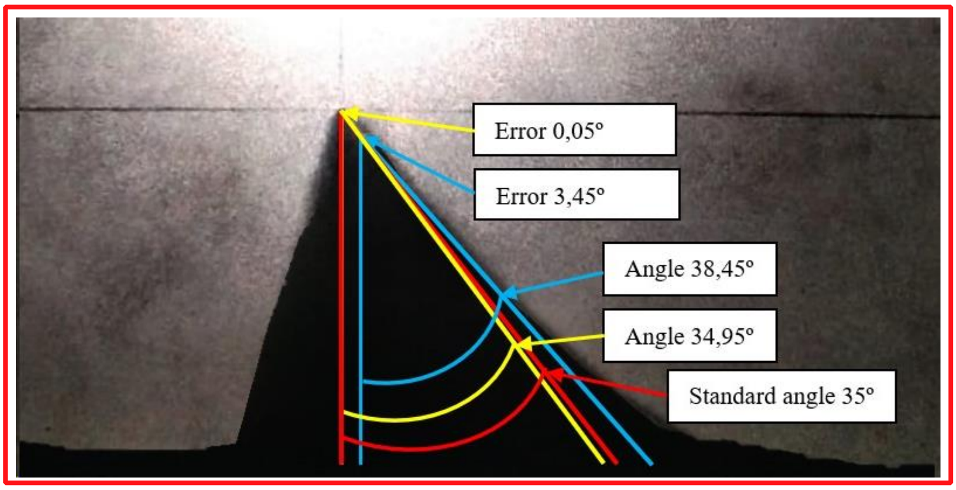

Fig. 15. Comparison of thread angle α errors before and after polishing at 110 min.

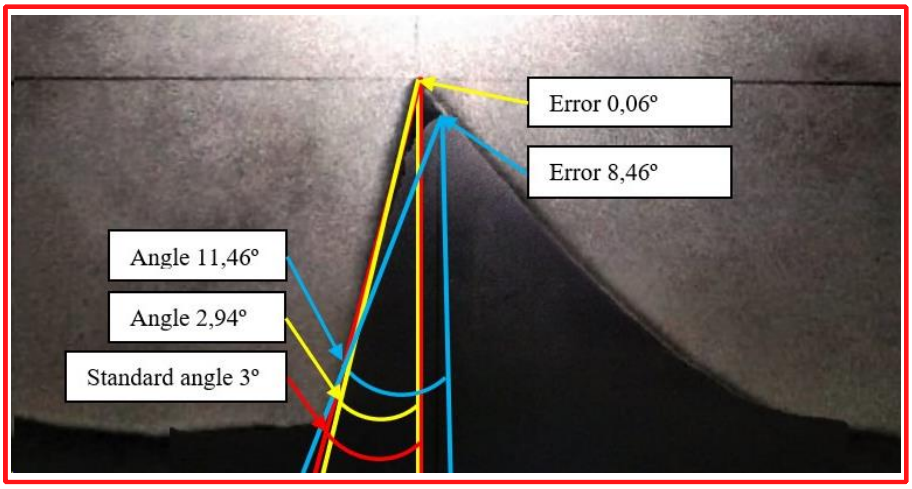

Fig. 16. Comparison of thread angle β errors before and after polishing at (a) 90 min.

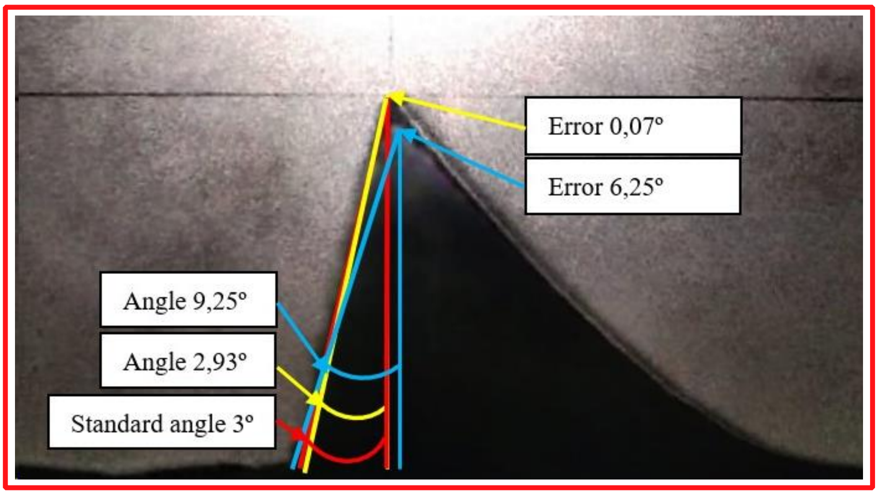

Fig. 17. Comparison of thread angle β errors before and after polishing at (b) 100 min.

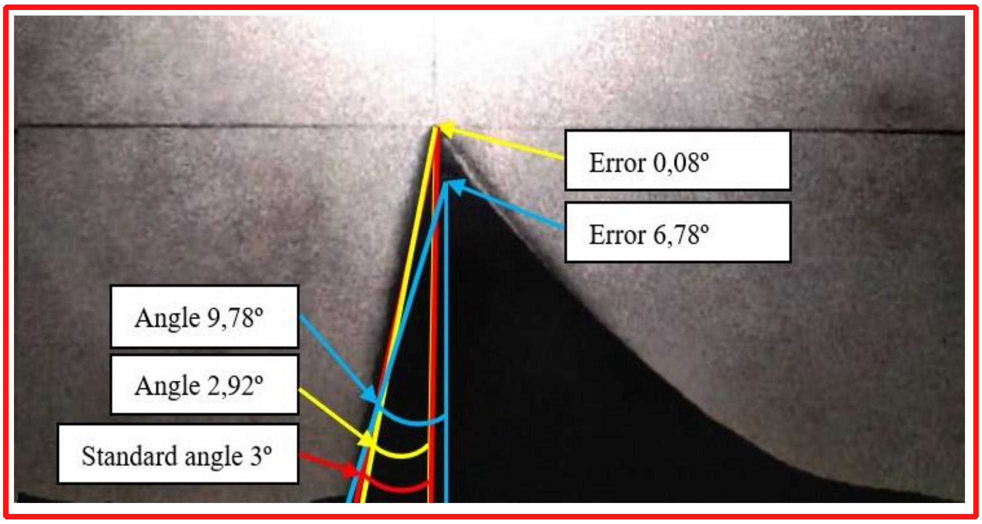

Fig. 18. Comparison of thread angle β errors before and after polishing at (c) 110 min.

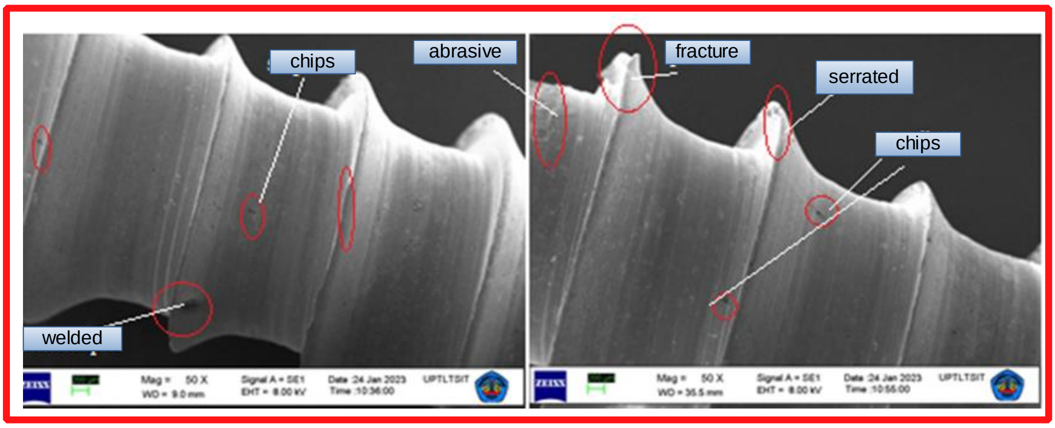

Fig. 19. Surface damages of cortical screws when polishing for 90 min.

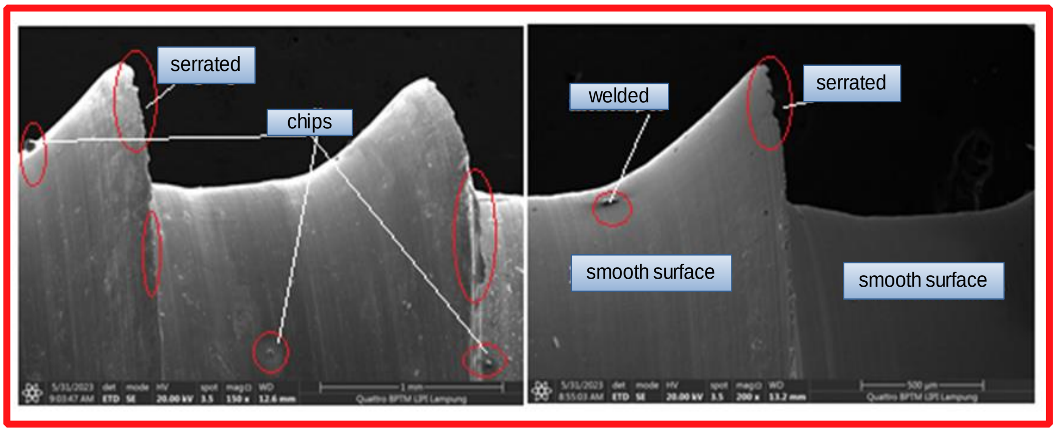

Fig. 20. Some surface damages of cortical screws and the smooth surface of the screw.

Figure 20 illustrates several surface damages on the cortical threaded surface. As shown in Figure 19, the types of surface damage, including serrated thread peaks, adhered material, and small chips on the surface, are nearly the same. Figure 20 also depicts a view of the threaded surface at the peaks and valleys, which appears very smooth. The threaded surface has undergone damage, and a significant portion of the surface has become smooth. Thus, the threading polishing process enhances surface smoothness while reducing surface damage.

IV. Conclusion

The research demonstrated that the polishing of Ti-6Al-4V ELI cortical screws effectively reduces surface damage; as a result, compared with the prepolishing conditions, the surface texture and smoothness after polishing are significantly improved. The polishing process results in a surface that facilitates the insertion of cortical screws, thereby potentially minimizing the risk of bone damage during surgical procedures and enhancing patient outcomes. Dimensional errors are maintained within an acceptable range, with a peak error of 1.2%. However, long polishing durations contribute to increased angular errors, particularly at the alpha and beta angles of the threads.

Despite some drawbacks, such as material reduction at thread peaks leading to increased beta angle errors, the benefits of a smooth surface are evident. Surface damage, including adhered materials and serrated peaks, is minimized, thereby highlighting the efficacy of optimized polishing techniques in improving the quality and reliability of orthopedic implants.

Future studies should focus on optimizing polishing parameters to achieve an ideal balance between material removal and maintaining dimensional precision. Investigating the application of these optimized techniques across different implant materials and complex geometries can further enhance their clinical utility and broaden their impact. These efforts would align with the overarching objective of advancing the quality and efficacy of biomedical implants.

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