Experimental Study on Surface Integrity of Ti6Al4V by Broaching

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A B S T R A C T

The performance of many parts in the airplane, aircraft engine and biomedical implants is highly related to their fatigue life, which is clearly depend on the condition of their surface integrity. The geometry parameters of broaching tools have an important influence on the surface integrity after broaching Ti6Al4V alloy. Therefore, this research studies the surface integrity of Ti6Al4V by broaching. The surface integrity is studied at different geometric parameters such as rake angles (α, and α0), clearance angles (β, and β0), and radius of the cutting edge (r0) in two last teeth of the broaching tool that perform chipping. The broached surface integrity is assessed in cases of surface roughness, microstructural, residual stresses, and micro hardness. These results show that the sample broached by tool number 1 (α = 18.4, β = 3.1, α0 = 45, β0 = 9, r0 = 0.02) had higher surface integrity because it was the smoothest surface and the thinnest deformed layer among the other samples. Since the main criterions in selection of the optimal tool are to create the smoothest surface and the least deformed layer depth in the broached sample, tool number 1 (α = 18.4, β = 3.1, α0 = 45, β0 = 9, r0 = 0.02) is suggested as the optimal tool.

doi: 10.5829/ije.2022.35.02b.24

1. INTRODUCTION

Broaching is a machining process widely used to produce some aspects because of the surface integrity state and high dimensional quality. Therefore, the surface integrity feature gained in broaching is very important in increasing the life of fatigue [1]. The Ti6Al4V alloy is extensively used in aircraft engine and medical implants which have high fatigue life and corrosion resistance are needed [2, 3]. Considering the working conditions of the turbine blade such as the presence of high centrifugal forces, and high temperatures during operation, the design of the broaching tool that creates the minimum residual stress on it is required [4].

Surface integrity is inherent or enhanced condition of a surface produced in machining or other surface generation operation [5]. Surface integrity states the performance and the quality of a machined part and contains of the metallurgical conditions (microstructure, phase transformation, etc.), mechanical properties (microhardness, residual stresses, etc.), and surface roughness [6]. In most cases, to prevent early failure and fatigue of the parts, the smoothest surface finish is desirable [7]. After any thermos-mechanical manufacturing operation such as machining processes, different features of surface integrity are affected [8].

Here, a history of research performed in the area of surface integrity of alloys by machining, has been presented. He and Zhang [9] investigated the influences of cutting factors on the surface integrity of broached TC9 alloy. Schulze et al. [10] used FE simulation to estimate created residual stress on the broached surface of SAE 5120 alloy. Kong et al. [11] studied the influences of cutting factors on saw-toothed chip formation of nickel-base alloy GH4169, using FE simulation. Jafarian et al. [12, 13] developed a robust method to predict and improve surface residual stress in the turning operation of Inconel718. Ortiz-de-Zarate et al. [14] presented an experimental and FE method analysis of surface integrity of broached Ti6Al4V. They studied the effect of cutting...
speed on cutting forces, chip morphology and surface integrity of broached Ti6Al4V. Kaway and Zhang [15] investigated surface integrity of Ti6Al4V in ball end milling process. Childs et al. [16] proposed a model that employs a failure criterion as a function of stress and temperature for Ti6Al4V. Bertolini et al. [17] evaluated the EBM Ti6Al4V machinability in terms of the relationship between the surface integrity with corrosion resistance and fatigue life. Khanjanzadeh et al. [18] proposed the optimal geometry for a broaching tool by using FE simulation which generates the lowest residual stress in the broached surface of the Ti6Al4V alloy. The mentioned studies showed that so far, relatively little study into surface integrity of Ti6Al4V by broaching has been done.

The main contribution of this manuscript is that for the first time, the experimental study is performed about the effect of broaching tool geometry on the surface integrity of Ti6Al4V. In our previous paper [18], based on finite element simulation and optimization using a genetic algorithm, it was shown that the optimal geometric parameters of the last two teeth of the broaching tool that perform chipping, depend on the percentage of effect of each of the temperature and effective strain factors.

2. MATERIALS AND METHODS

Figure 1 indicates the block diagram of the research method. In this research, based on the results of the Pareto diagram obtained in our previous paper [18], five tools with different optimal geometric characteristics were fabricated. Then the surface integrity of the broached samples was experimentally compared. Finally, the geometric parameters of the optimal broaching tool were introduced.

2.1. Materials

The test material is the grade 5 of Ti6Al4V. The wrought material was supplied in form of plates of 75mm × 25mm × 9mm and annealed at 955°C for one hour. Table 1 summarized the chemical composition of the material. The mechanical properties of the material are listed in Table 2. The final specimens were produced using the wire cut machine. Then the samples were mounted on a fixture. The test workpieces are indicated in Figure 2.

2.2. Broaching Tests

In our previous work [18], based on finite element simulation and optimization using a genetic algorithm, it was shown that the optimal geometric parameters of the last two teeth of the broaching tool that perform chipping, depend on the percentage of effect of the temperature and effective strain factors. In this study, based on the results of the Pareto diagram obtained in our previous research, five tools with different optimal geometric characteristics were constructed. Table 3 and Figure 3 show the geometric specifications of broaching tools based on our previous research work [18].

The broaching tools were made of a WC blade by a Robofil Charmilles wire cut machine. Thus, in total five tools were made. The cutting tools were mounted on a tool holder. The cutting speed of broaching operations was 3 m/min. Experimental tests were performed on an OKK PCV-55 3Axis CNC machine, 48”×22”. Figure 4 shows the broaching setup. Three repetitions were done for each cutting condition. So in total, fifteen tests were carried out.

| Table 1. Chemical composition of Ti6Al4V |
|------------------------------------------|
| Element | Ti  | Al  | V   | Fe  | Nb  | Cr  | Sn  | Si  | Mo  | W   | Mn  | Cu  | Zr  |
| Mass%   | Base| 5.65| 4.52| 0.18| 0.012| 0.011|<0.03|<0.06|<0.01|<0.02|<0.005| <0.005| <0.002 |

| Table 2. Mechanical properties of annealed Ti6Al4V [19] |
|-----------------------------------------------|
| Yield stress (MPa) | Ultimate stress (MPa) | Young's Module (GPa) | Micro hardness (HV) | Poisson’s ratio |
| 880              | 950             | 113.8           | 350              | 0.342           |
Figure 2. Test workpiece a) workpiece drawing, b) The workpieces mounted on the fixture

Figure 3. Broaching tool's drawing. (α: Rake angle of the first tooth, β: Clearance angle of the first tooth, α₀: Rake angle of the second tooth, β₀: Clearance angle of the second tooth, R: radius of the internal curvature of the gullet)

Figure 4. Broaching setup

TABLE 3. Geometric dimensions of tools (α: Rake angle of the first tooth, β: Clearance angle of the first tooth, α₀: Rake angle of the second tooth, β₀: Clearance angle of the second tooth, r₁: The radius of curvature of the gullet behind of the first tooth, r₂: The radius of curvature of the gullet behind of the second tooth)

| Tool’s No. | α   | β   | α₀  | β₀  | r₁ (mm) | r₂ (mm) |
|------------|-----|-----|-----|-----|---------|---------|
| 1          | 18.4° | 3.1° | 45° | 9°  | 0.02    | 3.62    |
| 2          | 18.4° | 3.1° | 45° | 9°  | 0.01    | 3.62    |
| 3          | 18.4° | 3.1° | 35° | 9°  | 0.01    | 3.62    |
| 4          | 18.4° | 3.1° | 35° | 8.2° | 0.01    | 3.62    |
| 5          | 18.4° | 3.1° | 35° | 8.4° | 0.01    | 3.62    |

2.3.1. Surface Roughness Analyze The surface roughness is measured at the center of each broached slot along the cutting direction using the contact method. Surface roughness measurements were done with a portable profilometer INNOVATEST® Model TR200 equipment. Table 4 indicates the conditions of surface roughness tests.

2.3.2. Residual Stresses Analyze The residual stresses were measured at the center of each broached slot using the X-Ray Diffraction (XRD) method via the sin²ψ technique. Measurements of residual stress were performed with a HAOYUAN Model DX-2700BH. Tilting was done along the cutting direction. Poisson’s ratio was assumed to be 0.342 and Young modulus 113.8 GPa [19].

2.3.3. Microstructural Images Analyze Grinding of the Ti6Al4V samples were done using up to 2000 SiC

TABLE 4. Surface roughness measurement parameters

| Parameter          | Value |
|--------------------|-------|
| Cutoff             | 0.8 mm|
| Tracing length     | 4 mm  |
| Radius of the probe tip | 0.05 µm |
| Tracing speed      | 0.5 mm/s|
| Resolution         | 0.005 µm|
gurt paper. Then the samples polished by 3 μm Al₂O₃ colloidal dispersion in distilled water. Finally, the polished samples were rinsed in distilled water and dried by a heater. To observe the microstructure of the samples, it is necessary to do chemical etching of the samples. Therefore, the specimens were reacted with an etchant (85% H₂O, 10% HF and 5% HNO₃) for 5 seconds. Then etched samples were washed in distilled water and then dried by a heater. The microstructure images were prepared by a UNION optical microscope and an scanning electron microscope Model JEOL840.

2. 3. 4. Micro Hardness Analyze Measurements of micro hardness were carried out using the Micromet 1 Buhler tester. The micro hardness test conditions are given in Table 5. Measurements were done on the middle line of the polished section surface of each. Indentations were made along a line consisted by six points, beginning the depth of 50 μm from the broached surface. The distance between two successive points kept enough to avoid measurement errors.

3. RESULTS AND DISCUSSION

3. 1. Surface Roughness The results of surface roughness measurements of the broached specimens are summarized in Table 6. As shown in Figures 5-7, the results of measuring the surface roughness of the broached specimens indicate that with an increase in r₀ (radius of the cutting edge of the second tooth) from 0.01 mm to 0.02 mm, the Rₐ and Rₜ of the broached surface decrease from 0.232 μm and 0.330 μm to 0.162 μm and 0.316 μm, respectively. An increase in the radius of the cutting edge reduces the penetration of the tool into the workpiece. As a result, the surface roughness is decreased. Also, with an increase in α₀ (second tooth rake angle) from 35 degrees to 45 degrees, the Rₐ and Rₜ of

| TABLE 5. The micro hardness test conditions |
|--------------------------------------------|
| Indenter   | Force | Loading time |
| Diamond pyramid | 100 grf | 15 s |

| TABLE 6. Surface roughness of specimens |
|------------------------------------------|
| Tool's No. | α    | β    | α₀  | β₀  | r₀ (mm) | Rₐ (μm) | Rₜ (μm) |
|-----------|------|------|-----|-----|---------|---------|---------|
| 1         | 18.4°| 3.1° | 45° | 9°  | 0.02    | 0.162   | 0.316   |
| 2         | 18.4°| 3.1° | 45° | 9°  | 0.01    | 0.232   | 0.330   |
| 3         | 18.4°| 3.1° | 35° | 9°  | 0.01    | 0.253   | 0.350   |
| 4         | 18.4°| 3.1° | 35.4°| 8.2°| 0.01    | 0.342   | 0.387   |
| 5         | 18.4°| 3.1° | 35° | 8.4°| 0.01    | 0.216   | 0.324   |
the broached surface decrease from 0.253 µm and 350 µm to 0.232 µm and 0.336 µm, respectively. The cause of these changes can be found according Merchant circle (Figure 8) and Equations (1) and (2) in mechanic of orthogonal cutting [20].

\[ F_c = \frac{t \cdot b \cdot \tau \cdot \cos(\beta - \alpha_0)}{\sin \phi \cdot \cos(\phi + \beta - \alpha_0)} \]  

(1)

\[ F_t = \frac{t \cdot r \cdot \sin(\beta - \alpha_0)}{\sin \phi \cdot \cos(\phi + \beta - \alpha_0)} \]  

(2)

where \( F_c \) is the cutting force, \( t \) is the thickness of chip before cutting, \( b \) is the cutting width, \( \tau \) is the yield shear stress, \( \beta \) is the friction angle, \( \alpha_0 \) is the rake angle, \( \phi \) is the shear angle, and \( F_t \) is the thrust force [20]. Increasing \( \alpha_0 \) reduces the thrust force and as a result, the surface roughness is decreased.

Moreover, with an increase in \( \beta_0 \) (clearance angle of the second tooth) from 8.4 degrees to 9 degrees, the \( R_a \) and \( R_z \) of the broached surface increase from 0.216 µm and 0.324 µm to 0.253 µm and 0.350 µm, respectively. Increasing \( \beta_0 \) reduces the contact of the tool with the workpiece surface. As a result, the surface roughness has increased.

3.2. Residual Stresses

The results of residual stress measurements of the broached specimens are shown in Table 7. In all cases, the residual stresses are compressive.

As shown in Figures 9-11, the results of measuring the residual stress of the broached specimens indicate that

![Figure 8. Merchant circle.](image)

**Figure 8.** Merchant circle. \( F_c \) is the cutting force, \( t \) is the thickness of chip before cutting, \( \beta \) is the friction angle, \( \alpha_0 \) is the rake angle, \( \phi \) is the shear angle, and \( F_t \) is the thrust force [20].

![Figure 9. Effect of radius of the cutting edge \((r_0)\) on residual stress](image)

**Figure 9.** Effect of radius of the cutting edge \((r_0)\) on residual stress

![Figure 10. Effect of rake angle of the second tooth \((\alpha_0)\) on residual stress](image)

**Figure 10.** Effect of rake angle of the second tooth \((\alpha_0)\) on residual stress

![Figure 11. Effect of clearance angle of the second tooth \((\beta_0)\) on residual stress](image)

**Figure 11.** Effect of clearance angle of the second tooth \((\beta_0)\) on residual stress

| Tool’s No. | \( \alpha \) (°) | \( \beta \) (°) | \( \alpha_0 \) (°) | \( \beta_0 \) (°) | \( r_0 \) (mm) | Residual stress (MPa) |
|-----------|-----------------|----------------|------------------|----------------|-------------|--------------------|
| 1         | 18.4            | 3.1            | 45               | 9              | 0.02        | 205               |
| 2         | 18.4            | 3.1            | 45               | 9              | 0.01        | 482               |
| 3         | 18.4            | 3.1            | 35               | 9              | 0.01        | 261               |
| 4         | 18.4            | 3.1            | 35.4             | 8.2            | 0.01        | 202               |
| 5         | 18.4            | 3.1            | 35               | 8.4            | 0.01        | 367               |
increasing $r_0$ (radius of the cutting edge of the second tooth) from 0.01 mm to 0.02 mm, causes a considerable decrease in the compressive residual stress created in the workpiece from 482 MPa to 205 MPa. Increasing the radius of the cutting edge reduces the penetration of the tool into the workpiece. As a result, reduces the residual stress created in broached surface.

Also, with increasing $\alpha_0$ (rake angle of the second tooth) from 35 degrees to 45 degrees, the compressive residual stress created in the workpiece increases from 261 MPa to 482 MPa. Increasing $\alpha_0$ increases the cutting force. As a result, the residual stress created in broached surface is increased. Moreover, with increasing $\beta_0$ (clearance angle of the second tooth) from 8.4 degrees to 9 degrees, the compressive residual stress created in the workpiece decreased from 367 MPa to 261 MPa. Increasing $\beta_0$ reduces the contact of the tool with the workpiece surface. As a result, the residual stress created in broached surface decreased.

3.5 Microstructural Analysis
Titanium alloys are classified according to the phases in their structure. Ti6Al4V alloy is the most important and widely used $\alpha + \beta$ titanium alloy. Aluminum and vanadium alloy elements are stabilizer of the alpha and beta phases, respectively. Figure 12 shows the phase diagram of Ti6Al4V [19]. Figure 13 depicts the microstructure of annealed material which contains a mixed $\alpha + \beta$ coaxial phase structure. The structure consists of $\alpha$-shaped plates (light) and intergranular beta (dark). Figures 14-18 show the microstructure of the surface perpendicular to the broached surface of the test specimens.

![Figure 12. Phase diagram of Ti6Al4V [19]](image1)

![Figure 13. Microstructure of annealed Ti6Al4V (Etching solution: HF10%, HNO3 5%, H2O 85%). a) Imaging by optic microscope. The structure consists of $\alpha$-shaped plates (light) and intergranular beta (dark). b) Imaging by scanning electron microscope (SEM). The structure consists of $\alpha$-shaped plates (dark) and intergranular beta (light)](image2)

![Figure 14. Microstructure of broached sample with tool No. 1 ($\alpha = 18.4$, $\beta = 3.1$, $\alpha_0 = 45$, $\beta_0 = 9$, $r_0 = 0.02$). The structure consists of $\alpha$-shaped plates (light) and intergranular beta (dark). (Etching solution: HF10%, HNO3 5%, H2O 85%)](image3)
Figure 15. Microstructure of broached sample with tool No. 2 ($\alpha = 18.4$, $\beta = 3.1$, $\alpha_0 = 45$, $\beta_0 = 9$, $r_0 = 0.01$). The structure consists of $\alpha$-shaped plates (light) and inter granular beta (dark). (Etching solution: HF10%, HNO$_3$ 5%, H$_2$O 85%)

Figure 16. Microstructure of broached sample with tool No. 3 ($\alpha = 18.4$, $\beta = 3.1$, $\alpha_0 = 35$, $\beta_0 = 9$, $r_0 = 0.01$). The structure consists of $\alpha$-shaped plates (light) and inter granular beta (dark). (Etching solution: HF10%, HNO$_3$ 5%, H$_2$O 85%)

Figure 17. Microstructure of broached sample with tool No. 4 ($\alpha = 18.4$, $\beta = 3.1$, $\alpha_0 = 35.4$, $\beta_0 = 8.2$, $r_0 = 0.01$). The structure consists of $\alpha$-shaped plates (light) and inter granular beta (dark). (Etching solution: HF10%, HNO$_3$ 5%, H$_2$O 85%)

Figure 18. Microstructure of broached sample with tool No. 5 ($\alpha = 18.4$, $\beta = 3.1$, $\alpha_0 = 35$, $\beta_0 = 8.4$, $r_0 = 0.01$). The structure consists of $\alpha$-shaped plates (light) and inter granular beta (dark). (Etching solution: HF10%, HNO$_3$ 5%, H$_2$O 85%)
As shown in Figures 14-18, in the thin layer below the broached surface, the grains are deformed perpendicular to the cutting direction. Comparing the microstructure of the broached specimens with the annealed specimen, despite the plastic deformation, no phase transformation can be detected; because of the cutting temperature is less than 800°C [18]. Table 8 summarized the results of the depth of deformed layer of broached specimens.

According to the Figures 19-21, the results of microstructural images of the broached specimens show that increasing \( r_0 \) (radius of the cutting edge of the second tooth) from 0.01 mm to 0.02 mm, causes a considerable decrease in the depth of the deformed layer in the broached specimen from 110 µm to 65 µm. Increasing the radius of the cutting edge reduces the penetration of the tool into the workpiece. As a result, the depth of the deformed layer reduced.

Also, with increasing \( \alpha_0 \) (rake angle of the second tooth) from 35 degrees to 45 degrees, the depth of the deformed layer in the broached sample increases from 80 µm to 110 µm. Increasing \( \alpha_0 \) increases the cutting force. As a result, the depth of the deformed layer is increased. Moreover, by increasing \( \beta_0 \) (clearance angle of the second tooth) from 8.4 degrees to 9 degrees, the depth of the deformed layer in the broached sample decreases from 95 µm to 80 µm. Increasing \( \beta_0 \) reduces the contact of the tool with the workpiece surface. As a result, the depth of deformed in workpiece decreased.

### Table 8. The depth of deformed layer of broached specimens

| Tool’s No. | \( \alpha \) | \( \beta \) | \( \alpha_0 \) | \( \beta_0 \) | \( r_0 \) (mm) | Depth of deformed layer (µm) |
|-----------|--------|--------|--------|--------|--------|------------------|
| 1         | 18.4°  | 3.1°   | 45°    | 9°     | 0.02   | 65               |
| 2         | 18.4°  | 3.1°   | 45°    | 9°     | 0.01   | 110              |
| 3         | 18.4°  | 3.1°   | 35°    | 9°     | 0.01   | 80               |
| 4         | 18.4°  | 3.1°   | 35.4°  | 8.2°   | 0.01   | 65               |
| 5         | 18.4°  | 3.1°   | 35°    | 8.4°   | 0.01   | 95               |

### 3.4. Micro Hardness Profiles

Figure 22 shows the effect of the geometric parameters of the tool on the micro hardness profiles of the broached specimens. These results show that the micro hardness of the samples increases at the broached surface and gradually decreases with an increase in the distance from the surface. Table 9 shows the maximum micro hardness of broached specimens.

According to Figures 23-25, the micro hardness measurement results of the broached workpieces show that increasing \( r_0 \) (radius of the cutting edge of the second tooth) from 0.01 mm to 0.02 mm, decreases the maximum micro hardness created in the workpiece from 401 Vickers to 380 Vickers. Increasing the radius of the cutting edge reduces the penetration of the tool into the workpiece.
workpiece. As a result, reduces the strain hardening in the broached workpiece. Also, by increasing $\alpha_0$ (angle of the second tooth chip) from 35 degrees to 45 degrees, the maximum micro hardness created in the workpiece has increased from 383 Vickers to 401 Vickers. Increasing $\alpha_0$ increases the cutting force. As a result, strain hardening in the broached workpiece increased.

Moreover, by increasing $\beta_0$ (clearance angle of the second tooth) from 8.4 degrees to 9 degrees, the maximum micro hardness created in the workpiece decreased from 390 Vickers to 383 Vickers. Increasing $\beta_0$ reduces the contact of the tool with the workpiece surface. As a result, the strain hardening in the broached workpiece decreased.

**TABLE 9. The maximum micro hardness of workpieces**

| Tool's No. | $\alpha$ | $\beta$ | $\alpha_0$ | $\beta_0$ | $r_0$(mm) | Maximum micro hardness (HV) |
|------------|----------|---------|------------|-----------|------------|-----------------------------|
| 1          | 18.4°    | 3.1°    | 45°        | 9°        | 0.02       | 380                         |
| 2          | 18.4°    | 3.1°    | 45°        | 9°        | 0.01       | 401                         |
| 3          | 18.4°    | 3.1°    | 35°        | 9°        | 0.01       | 383                         |
| 4          | 18.4°    | 3.1°    | 35.4°      | 8.2°      | 0.01       | 380                         |
| 5          | 18.4°    | 3.1°    | 35°        | 8.4°      | 0.01       | 390                         |
The results of the surface integrity investigation of broached samples are shown in Table 10. These results show that the sample broached by tool number 1 (α = 18.4, β = 3.1, α₀ = 45, β₀ = 9, r₀ = 0.02) has higher surface integrity because it has the smoothest surface and the thinnest deformed layer, is less thick than the other samples. Since the main criteria in selecting the optimal tool are to create the smoothest surface and the least deformed layer depth in the broached sample, tool number 1 (α = 18.4, β = 3.1, α₀ = 45, β₀ = 9, r₀ = 0.02) is suggested as the optimal tool.

### TABLE 10. Results of the surface integrity investigation of broached samples

| Tool’s No. | Ra (µm) | Rz (µm) | Residual stress (MPa) | Depth of deformed layer (µm) | Maximum micro hardness (HV) |
|------------|---------|---------|-----------------------|-----------------------------|-----------------------------|
| 1          | 0.162   | 0.316   | 205                   | 65                          | 380                         |
| 2          | 0.232   | 0.330   | 482                   | 110                         | 401                         |
| 3          | 0.253   | 0.350   | 202                   | 80                          | 383                         |
| 4          | 0.342   | 0.387   | 261                   | 65                          | 380                         |
| 5          | 0.216   | 0.324   | 367                   | 95                          | 390                         |

### 4. CONCLUSION

This study investigates the surface integrity of Ti6Al4V by broaching. The different surface integrity aspects including: surface roughness, residual stress, microstructural, and micro hardness, are investigated.

- The results of measuring the surface roughness of the broached specimens indicate that an increase in r₀ (radius of the cutting edge of the second tooth) from 0.01 mm to 0.02 mm, decrease the Rₐ and R₂ of the broached surface from 0.232 µm and 0.330 µm to 0.162 µm and 0.316 µm, respectively. Increasing the radius of the cutting edge reduces the penetration of the tool into the workpiece. As a result, reduces the residual stress created in broached surface. Also, with increasing α₀ (rake angle of the second tooth) from 35 degrees to 45 degrees, the Rₐ and R₂ of the broached surface decrease from 0.253 µm and 0.350 µm to 0.232 µm and 0.336 µm, respectively. Increasing α₀ reduces the thrust force and as a result, the surface roughness is decreased. Moreover, with increasing β₀ (clearance angle of the second tooth) from 8.4 degrees to 9 degrees, the Rₐ and R₂ of the broached surface increase from 0.216 µm and 0.324 µm to 0.253 µm and 0.350 µm, respectively. Increasing β₀ reduces the contact of the tool with the workpiece surface. As a result, the surface roughness increased.

- The results of measuring the residual stress of the broached specimens indicate that increasing r₀ (radius of the cutting edge of the second tooth) from 0.01 mm to 0.02 mm, causes a considerable decrease in the compressive residual stress created in the work piece from 482 MPa to 205 MPa. Increasing the radius of the cutting edge reduces the penetration of the tool into the work piece. As a result, reduces the residual stress created in broached surface. Also, with increasing α₀ (rake angle of the second tooth) from 35 degrees to 45 degrees, the compressive residual stress created in the work piece increases from 261 MPa to 482 MPa. Increasing α₀ increases the cutting force. As a result, the residual stress created in broached surface is increased. Moreover, with increasing β₀ (clearance angle of the second tooth) from 8.4 degrees to 9 degrees, compressive residual stress created in the work piece decreases from 367 MPa to 261 MPa. Increasing β₀ reduces the contact of the tool with the workpiece surface. As a result, the residual stress created in broached surface decreased.

- The results of microstructural images of the broached specimens show that increasing r₀ (radius of the cutting edge of the second tooth) from 0.01 mm to 0.02 mm, causes a considerable decrease in the depth of the deformed layer in the broached specimen from 110 µm to 65 µm. Increasing the radius of the cutting edge reduces the penetration of the tool into the work piece. As a result, reduces the depth of the deformed layer. Also, with increasing α₀ (rake angle of the second tooth) from 35 degrees to 45 degrees, the depth of the deformed layer in the broached sample increases from 80 µm to 110 µm. Increasing α₀ increases the cutting force. As a result, the depth of the deformed layer is increased. Moreover, by increasing β₀ (clearance angle of the second tooth) from 8.4 degrees to 9 degrees, the depth of the deformed layer in the broached sample decreases from 95 µm to 80 µm. Increasing β₀ reduces the contact of the tool with the workpiece surface. As a result, the depth of deformed in workpiece decreased.

- The micro hardness measurements results of the broached workpieces show that increasing r₀ (radius of the cutting edge of the second tooth) from 0.01 mm to 0.02 mm, decreases the maximum micro hardness created in the workpiece from 401 Vickers to 380 Vickers. Also, with increasing α₀ (rake angle of the second tooth) from 35 degrees to 45 degrees, the maximum micro hardness created in the workpiece has increased from 383 Vickers to 401 Vickers. Increasing α₀
increases the cutting force. As a result, strain hardening in the broached workpiece is increased. Moreover, by increasing $\beta_0$ (clearance angle of the second tooth) from 8.4 degrees to 9 degrees, the maximum micro hardness created in the workpiece decreases from 390 Vickers to 383 Vickers. Increasing $\beta_0$ reduces the contact of the tool with the workpiece surface. As a result, the strain hardening in the broached workpiece decreased.

- These results show that the sample broached by tool number 1 ($\alpha = 18.4$, $\beta = 3.1$, $\alpha_0 = 45$, $\beta_0 = 9$, $m = 0.02$) has higher surface integrity because it has the smoothest surface and the thinnest deformed layer among the other samples. Since the main criterions in selecting the optimal tool are to create the smoothest surface and the least deformed layer depth in the broached sample, tool number 1 ($\alpha = 18.4$, $\beta = 3.1$, $\alpha_0 = 45$, $\beta_0 = 9$, $m = 0.02$) is suggested as the optimal tool.

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چکیده
کارآیی بسیاری از قطعات هواپیما، موتور فضاپیما و ایمپلنت‌های پزشکی به شدت با عمر خستگی آنها و ضعیت پکیج‌ریک فلز آلیاژ Ti6Al4V شناخته شده‌است. این تحقیق، یکپارچگی سطح آلیاژ Ti6Al4V پکیج‌ریک به طور تجربی مورد بررسی قرار گرفته است. پارامترهای هندسی، شامل نرخ نخستین و ثانویه زاویه براده (α و β)، زاویه آزاد (0α و 0β) و شعاع نوک ابزار (R0) در دو دندانه انتهایی ابزار خانکشی که براده پکیج‌ریک دارد، بر یکپارچگی سطح آلیاژ Ti6Al4V کاربرد دارد. پارامترهای هندسی ابزار شامل نرخ نخستین و ثانویه زاویه براده (α و β)، زاویه آزاد (0α و 0β) و شعاع نوک ابزار (R0) در دو دندانه انتهایی ابزار خانکشی که براده پکیج‌ریک دارد، بر یکپارچگی سطح آلیاژ Ti6Al4V کاربرد دارد.

یکپارچگی سطح پکیج‌ریک در موارد صافی سطح، تنظیم پاپیل‌های سطح، تغییر شکل و کمترین ضخامت لایه تغییر فرم در نمونه‌ها رخ می‌دهد. ابزار شماره 1 (α = 18.4°, β = 3.1°, α0 = 45°, β0 = 9°, R0 = 0.02mm) بهترین پارامترهای ابزاری برای ایجاد صاف‌ترین سطح و کمترین ضخامت لایه تغییر فرم در نمونه‌ها به‌نظر می‌رسد. ابزار شماره 1 به عنوان ابزار بهینه پیشنهاد شده است.