Preparation of a titanium alloy outer ring self-lubricating spherical plain bearing by a two-step extrusion forming process

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Received: 16 March 2022 / Accepted: 25 June 2022 / Published online: 8 July 2022 © The Author(s), under exclusive licence to Springer-Verlag London Ltd., part of Springer Nature 2022

Abstract
Self-lubricating spherical plain bearings are a key component widely used in the aerospace field. The spherical plain bearing made of titanium alloy has a lighter weight and better corrosion resistance. To manufacture the outer ring of a self-lubricating spherical plain bearing with titanium alloy, a two-step extrusion forming process was proposed. Taking a GE15DE1TK spherical plain bearing as an example, the finite element simulation model of the forming process was established, the forming test was carried out, and the outer ring of a self-lubricating spherical plain bearing made by TC4 titanium alloy was successfully prepared. The results show that forming defects such as over extrusion and insufficient extrusion can be improved by optimizing the die structure, the size of the outer ring blank, and the lubrication conditions. The forming parameters for the GE15DE1TK spherical plain bearing are given. The prepared spherical plain bearing can be used directly without other processes to correct no-load rotational breakaway torque.

Keywords Self-lubricating spherical plain bearing · Extrusion forming process · Titanium alloy · Precision forming

1 Introduction
Self-lubricating spherical plain bearings have the advantages of large bearing capacity, long service life, compact structure, and no maintenance. It is a key supporting component of many important pieces of equipment, and it is widely used in aerospace fields such as aircraft control systems, landing gears, and rotor systems [1–3]. Bearing companies such as Kamatic and RBC carried out research on the design and manufacturing technology of self-lubricating spherical plain bearings as early as the 1950s, with mature design methods and manufacturing processes [4]. In recent years, with the increasing service demand of marine and aviation aircraft, the self-lubricating spherical plain bearing has been in service for a long time in the marine atmospheric environment. Hence, bearings are prone to corrosion, locking and other failure forms, which seriously affects the mobility and safety of aviation aircraft and puts forward higher requirements for
the lightweight and corrosion resistance of self-lubricating spherical plain bearings [5, 6].

Titanium alloys have excellent properties, such as low density, high specific strength, and corrosion resistance. It is widely used in structural parts such as aircraft fuselages and engines. It is the preferred material for lightweight self-lubricating spherical plain bearings [7, 8]. However, titanium alloys have a large yield ratio, narrow plastic deformation range, and small elastic modulus, so the forming accuracy is difficult to control [9]. To realize the precision forming of titanium alloys, there are two common processes: precision forging and isothermal superplastic forging, which are mainly used for the development of gas cylinders and tanks in the aerospace field [10]. These include Ti-6Al-4V and Ti-5Al-2.5Sn ELI titanium alloy pressure vessels; 0t4-1 and BT5-1 fuel tanks in progress detectors; Ta7 Eli titanium alloy cryogenic gas cylinders in xx-3a and xx-5 launch vehicles [11]; Ti-6Al1-4V titanium alloy N2H4 fuel tanks [12].

However, these precision forming processes for titanium alloys need to be heated to more than 700 °C. Due to the material characteristics of titanium alloys, titanium alloy cold-formed components are generally found in single curvature parts with large bending radii that can easily form [13]. The self-lubricating layer is adhered to the outer ring of the self-lubricating spherical plain bearing before forming. The titanium alloy outer ring must be formed at room temperature to ensure the self-lubricating performance and bonding performance of the self-lubricating layer [14, 15].

In addition, in the existing extrusion forming process of a self-lubricating spherical plain bearing, the self-lubricating gasket is often over-extruded [16, 17], which reduces the service life and the self-lubricating effect of the bearing [18, 19]. After the bearing is formed, the rotational breakaway torque of the bearing needs to be further adjusted with the aid of other processes, which increases the production cost [20]. Therefore, the existing forming process needs to be further improved to be suitable for the forming of titanium alloy outer ring self-lubricating spherical plain bearings. Due to the above limitations, the precision forming process of the titanium alloy outer ring at room temperature is very difficult, and there are few research reports.

In this paper, a two-step extrusion forming process was proposed, and the forming characteristics and outer ring deformation law of the process were analyzed by means of finite element simulation and experiment. The main factors affecting the forming results were determined, and the forming process parameters were optimized. A self-lubricating spherical plain bearing with a titanium alloy outer ring was prepared by a forming test. This study provides theoretical and data support for the development of titanium alloy outer ring self-lubricating spherical plain bearings.

2 Principle of the two-step extrusion forming process

The forming model is shown in Fig. 1. The main forming parts include the upper die, bearing outer ring bonded with gasket, bearing inner ring, and lower die. The working surface of the upper die is a conical surface with a certain angle (α), and the maximum cone diameter (s) needs to be determined according to the size of the bearing. The main dimensions of the outer ring blank include the height (H), outer diameter (D), inner diameter (d), and gasket thickness (h). To facilitate the processing and bonding of the gasket, the shape of the outer ring blank was designed as a circular ring, and the inner ring and the lower die did not participate in the deformation.

Fig. 1 Forming model of a self-lubricating spherical plain bearing
The forming principle is shown in Fig. 2. The positioning mandrel is used to fix the position of the inner and outer rings of the bearing. The upper die moves up and down according to the specified forming distance to realize the first forming. Then, the outer ring is turned over 180° and repositioned on the lower die, and the upper die moves up and down again to realize the second forming.

As shown in Fig. 3, referring to the dimensions of the GE15DE1TK spherical plain bearing, a finite element model with a two-step extrusion forming process was established by DEFORM3D software. The outer ring material was TC4 titanium alloy, and the mechanical property parameters are shown in Table 1. The stress–strain curve of TC4 was measured through the tensile test, as shown in Fig. 4. The finite element model was an axisymmetric mode, and the outer ring had large deformation, so the elastic–plastic model was adopted. The friction was set as the Coulomb friction model. The element type was tetrahedron, with 5012 elements and 5248 nodes.

### 3 Analysis of the main factors affecting the forming results

Figure 5 shows bearings with good forming quality and typical defects. Common forming defects include insufficient extrusion and over extrusion [21]. These defects can affect the rotational breakaway torque of the bearing and reduce the service life of the bearing. Titanium alloy has a large yield strength and small elastic modulus. These forming defects are more likely to occur in the cold forming process. The die structure, forming distance, and outer ring blank size directly affect the deformation process of titanium alloy. For the extrusion process, the deterioration of lubrication conditions in actual production was also prone to forming defects [22]. Under high forming pressure, it is difficult to ensure good lubrication conditions between the blank and the die, while poor lubrication increases the wear of the die and workpiece. Therefore, the lubrication condition is also an important factor to be considered. The main reasons affecting the forming results are the die structure, forming distance, outer ring blank size, and lubrication conditions.

The influence degree of each factor on the forming result was analyzed by orthogonal testing, and the forming distance ($L$), die angle ($\alpha$), inner diameter ($d$), the thickness of the outer ring ($t$), and friction coefficient ($f$) were set as

| Table 1 TC4 mechanical property parameters |
|-------------------------------------------|
| Material | Young’s modulus (GPa) | Poisson’s ratio | Density (g/cm³) |
|-----------|-----------------------|----------------|----------------|
| TC4       | 109                   | 0.34           | 4.44           |
the influencing factors. An L16(4^5) orthogonal test table was adopted, and four levels were set for each factor, as shown in Tables 2 and 3. In this paper, the track radius of the inner surface of the outer ring was used as the forming quality evaluation index [23]. A schematic diagram of the track radius of the inner surface of the outer ring is shown in Fig. 6.

where \( R_i \) is the radius of the inner surface of the outer ring after forming; \( R_J \) is the target value of the inner surface radius, which is equal to the sum of the inner ring radius and gasket thickness, and the gasket thickness is set as 0.4 mm [24]; \( F_{err} \) indicates the forming accuracy. The smaller \( F_{err} \) is, the closer the radius of the inner surface after forming is to the target size, so the forming accuracy is higher.

Excessive forming force can improve the design requirements of forming equipment and dies, which is not conducive to the precision forming of bearings. The maximum forming pressure is selected as the second evaluation index.

The orthogonal test results were analyzed by range analysis.

\[
T_i = \max \left\{ \frac{K_{im}}{n} \right\} - \min \left\{ \frac{K_m}{n} \right\}
\]

where \( K_{im} \) is the average value of the evaluation index at a certain level of a factor, \( K_m \) is the average value of the evaluation index at other levels of a factor, and \( T_i \) is the difference between the average value of the maximum evaluation index and the average value of the minimum evaluation index at all levels under a factor. The greater the \( T_i \) value is, the greater the impact of the factor on the evaluation index.

The influence of various factors on the forming accuracy and maximum forming force range is shown in Fig. 7. The order of forming accuracy \( T_i \) is forming distance > outer ring blank thickness > friction coefficient > inner surface diameter > die angle. The order of forming pressure \( T_i \) is outer ring blank thickness > die angle > forming distance > friction coefficient > inner surface diameter. This shows that the largest factors affecting the forming accuracy and forming pressure are the forming distance and outer ring blank thickness, respectively. Due to the coupling effect of various parameters, it is difficult to quantitatively analyze the influence of various factors on the deformation in the orthogonal test results. Therefore, the key factors are quantitatively analyzed through a single-factor experiment.

### 4 Influence of forming distance and die angle on forming results

The lateral displacement of the outer ring under different forming distances and die angles is shown in Fig. 8. Comparing Fig. 8a with Fig. 8b, the forming distance increases from 2 to 5 mm, and the maximum transverse displacement of the inner surface of the outer ring increases from 0.74 to 2.85 mm, indicating that increasing the forming distance can significantly increase the lateral displacement of the outer ring.
The maximum lateral displacement of the inner surface in Fig. 8c is 0.39 mm, which is smaller than that in Fig. 8a, indicating that increasing the die angle will reduce the lateral displacement of the outer ring. Therefore, a small die angle should be used to match a small forming distance, and the inner diameter of the outer ring can be designed to be close to the outer diameter of the inner ring. Insufficient extrusion defects easily appear under this cooperation (Fig. 8a, c). When the forming distance is large, selecting a smaller die angle easily produces over extrusion defects (Fig. 8b). The extrusion degree at both ends of the outer ring can be improved by increasing the inner diameter of the outer ring or increasing the die angle (Fig. 8d).

The relationship between the forming distance, forming accuracy, and forming pressure under two die angles is shown in Fig. 9. When the die angle is 70°, with increasing forming distance, $F_{\text{err}}$ decreases from 0.907 to 0.233, indicating that increasing the forming distance can improve the forming accuracy. When the die angle is 60°, $F_{\text{err}}$ decreases and then increases. The forming accuracy with a forming distance of 4 mm is the highest, and $F_{\text{err}}$ is 0.08. The reason may be that insufficient extrusion is caused by a forming distance that is too small under the same die angle, and over extrusion is caused by a forming distance that is too large. Both cases will reduce the forming accuracy. Therefore, reducing the die angle can

| No | Forming distance (mm) | Angle of die (°) | Internal diameter (mm) | Thickness (mm) | Friction coefficient | $F_{\text{err}}$ (mm) | Max forming pressure (kN) |
|----|----------------------|-----------------|-----------------------|---------------|---------------------|----------------------|--------------------------|
| 1  | 2                    | 40              | 23.8                  | 2             | 0.2                 | 0.183                | 95.11                    |
| 2  | 2                    | 50              | 24.3                  | 3             | 0.3                 | 0.138                | 204.74                   |
| 3  | 2                    | 60              | 24.8                  | 4             | 0.4                 | 0.5                  | 185.85                   |
| 4  | 2                    | 70              | 25.3                  | 5             | 0.5                 | 0.931                | 176.47                   |
| 5  | 3                    | 40              | 24.3                  | 4             | 0.5                 | 0.288                | 505.87                   |
| 6  | 3                    | 50              | 23.8                  | 5             | 0.4                 | 0.389                | 555.94                   |
| 7  | 3                    | 60              | 25.3                  | 2             | 0.3                 | 0.57                 | 61.2                     |
| 8  | 3                    | 70              | 24.8                  | 3             | 0.2                 | 0.473                | 62.02                    |
| 9  | 4                    | 40              | 24.8                  | 5             | 0.3                 | 0.512                | 729.5                    |
| 10 | 4                    | 50              | 23.8                  | 4             | 0.2                 | 1.153                | 338.89                   |
| 11 | 4                    | 60              | 25.3                  | 3             | 0.5                 | 0.08                 | 188.32                   |
| 12 | 4                    | 70              | 24.3                  | 2             | 0.4                 | 0.13                 | 59.38                    |
| 13 | 5                    | 40              | 25.3                  | 3             | 0.4                 | 0.809                | 384.33                   |
| 14 | 5                    | 50              | 24.8                  | 2             | 0.5                 | 0.674                | 162.85                   |
| 15 | 5                    | 60              | 24.3                  | 5             | 0.2                 | 1.093                | 274.49                   |
| 16 | 5                    | 70              | 23.8                  | 4             | 0.3                 | 0.645                | 156.06                   |

Fig. 6 Schematic diagram of track radius of inner surface of outer ring

Fig. 7 Influence of various factors (forming distance, die angle, inner diameter, thickness of outer ring, and friction coefficient) on forming accuracy and maximum forming force range
obtain the best forming accuracy under a small forming distance.

When the die angle is 60°, the forming pressure will increase significantly with increasing forming distance before the forming distance is 4 mm, which mainly comes from the friction between the outer ring and the die, and the plastic deformation of the outer ring itself. The larger the forming distance is, the greater the forming pressure needed, and the maximum forming pressure after 4 mm is basically the same. The reason may be that the contact area between the outer ring and the die is no longer increased, and the friction force does not increase significantly after the outer ring is deformed. When the die angle decreases from 70° to 60°, the forming pressure increases by approximately 30%. Reducing the die angle will significantly increase the forming pressure.

5 Influence of the outer ring thickness and forming distance on the forming results

The lateral displacement of the outer ring under different outer ring thicknesses and forming distances is shown in Fig. 10. The maximum lateral displacement of the middle part of the outer ring in Fig. 10a is 0.22 mm, and the
maximum lateral displacement of both ends is 1.33 mm. As the outer ring thickness increases to 5 mm, the maximum lateral displacements of the middle and both ends are 0.63 and 1.48 mm, respectively (Fig. 10b). This shows that the thickness of the outer ring is small, the blank is easily deformed, and the diameter of the outer ring will be reduced after the bearing is formed. The use of a thinner outer ring blank can result in the reduction in diameter and can cooperate with the smaller inner diameter of the outer ring to ensure the rotational breakaway torque of the bearing. It is easy to produce over extrusion defects when cooperating with a large forming distance (Fig. 10c). As the thickness of the outer ring increases, the part in contact with the die will produce large plastic deformation (Fig. 10b, d). Overall, the outer ring blank will produce large upsetting deformation, which easily produces insufficient extrusion and asymmetric defects (Fig. 10b, d). Therefore, on the premise of ensuring the machining allowance, the thinner outer ring blank should be used as much as possible.

The relationship between the blank thickness of the outer ring and the forming accuracy and the maximum forming pressure under two forming distances is shown in Fig. 11. When the forming distance is 3 mm, the forming accuracy decreases first and then increases. When the thickness is 3 mm, the forming accuracy is the worst. The reason may be that when the thickness is less than 3 mm, the bending deformation degree of the outer ring is large, and matching with a small forming distance can improve the forming accuracy. When the forming distance is 4 mm, the forming accuracy first increases and then decreases, and the forming accuracy with a thickness of

![Diagram](image_url)
3 mm reaches the highest value. The reason may be that if the outer ring thickness is too small at a large forming distance, it will produce transition extrusion and then form over extrusion defects, which reduces the forming accuracy. Increasing the blank thickness can improve the over extrusion defect to a certain extent, so the forming accuracy is improved. As the thickness increases to 3 mm, the outer ring produces a large upsetting deformation under the influence of a large forming distance, resulting in a gradual reduction in the forming accuracy. The forming accuracy is the highest when the outer ring thickness is 3 mm and the forming distance is 4 mm.

At forming distances of 3 and 4 mm, with increasing outer ring thickness, the maximum forming pressure increases from 93.48 and 82.25 to 516.13 and 284.16 kN, respectively, indicating that increasing the outer ring blank thickness will significantly increase the forming pressure. The reason is that the bending deformation capacity decreases with increasing outer ring thickness, which increases the upsetting deformation and contact area of the die. This increases the friction and leads to a large forming pressure because the titanium alloy easily bonds with the die. When the thickness of the outer ring is less than 3 mm, the difference between the maximum forming pressures of 3 and 4 mm is less than 20%. When the thickness of the outer ring reaches 5 mm, the difference between the maximum forming pressure is approximately 80%, indicating that the greater the thickness of the outer ring is, the more significant the influence of the forming distance on the forming pressure.

6 Influence of the friction coefficient and outer ring thickness on the forming results

The lateral displacement of the outer ring under different friction coefficients and outer ring thicknesses is shown in Fig. 12. In Fig. 12a, the deformation size of the middle part of the outer ring is approximately 0.61 mm, and the two ends are approximately 1.84 mm. With the outer ring thickness increasing to 4 mm, the deformation size of the middle part is approximately 0.92 mm, and the two ends are approximately 1.84 mm (Fig. 12c). This shows that increasing the outer ring thickness will reduce the bending deformation degree of the outer ring and increase the diameter shrinkage of the outer ring. As the friction coefficient increases from 0.2 to 0.5, the deformation size of the middle part of the outer ring decreases from 0.61 to 0.57 mm (Fig. 12b). When the thickness is larger (4 mm), the friction coefficient increases (Fig. 12d). The deformation sizes of both ends of the outer ring are 1.68 and 1.96 mm, which reduces the symmetry of both ends. The reason may be that the larger friction coefficient enhances the upsetting of the outer ring.

The influence of the friction coefficient on the forming accuracy and maximum forming pressure under two kinds of outer ring thicknesses is shown in Fig. 13. When the thickness of the outer ring is 3 mm, the friction coefficient has little effect on the forming accuracy. However, when the thickness of the outer ring increases to 4 mm, the forming accuracy decreases. The reason may be that increasing the thickness of the outer ring reduces the bending deformation of the blank, resulting in excessive outer diameter shrinkage, which reduces the forming accuracy. When the outer ring thickness is 4 mm, the forming accuracy decreases first and then increases with the friction coefficient. The forming accuracy is the worst when the friction coefficient is 0.3, and the forming accuracy is higher when the friction coefficient is larger. This may be the result of coupling with other forming process parameters, indicating that the friction coefficient does not necessarily have a negative effect on the forming accuracy for the two-step extrusion forming process. This is a difference between this process and other processes [25].

When the outer ring thickness is small (3 mm), the maximum forming pressure is positively correlated with the friction coefficient. When the outer ring thickness is large (4 mm), the maximum forming pressure first increases significantly with increasing friction coefficient but then decreases slightly after the friction coefficient is 0.3. The reason may be that when the outer ring thickness is large, the bending deformation of the titanium alloy decreases and the plastic deformation increases. When the friction coefficient increases to a certain extent, it no longer plays a major role in the forming pressure. A large friction force will increase the wear of the die and reduce the service life. Therefore, it is necessary to improve the lubrication state between the die and blank and reduce the friction coefficient.

7 Forming test

According to the results of finite element simulation analysis, the optimized bearing forming parameters were determined: outer diameter 30 mm, inner diameter 24.4 mm,
height 12 mm, die angle 70° and forming distance 4.1 mm. The inner ring material was G95Cr18 steel, and the materials of the lower die and upper die were carburized 40Cr. The forming equipment was a TOX punch machine (maximum punching pressure 200 kN), and the lubricating medium was graphite grease. Figure 14 shows the outer ring blank, die, and bearing samples after forming.

The bearing section and no-load rotational breakaway torque are shown in Fig. 15. The bearing with non-optimized forming process parameters has serious insufficient extrusion defects, and the matching quality of the optimized bearing has been significantly improved. The no-load starting torque of the non-optimized bearing sample is less than 0.05 N·m, and the optimized no-load starting torque is approximately 0.13 N·m, which meets the requirements of 0.0–0.5 N·m in the standard.

In the manufacturing process of existing self-lubricating bearings, rolling is generally required to adjust the no-load rotational breakaway torque after bearing extrusion [26]. Compared with traditional processing methods, this process can directly prepare self-lubricating plain bearings that meet the requirements of no-load rotational breakaway torque standards.

The variation curve of forming pressure with forming distance in the test and simulation is shown in Fig. 16.
The figure shows that the pressure-distance curves of the test and simulation are similar, which proves that the accuracy of the simulation is high. According to the change trend of the forming force, the deformation process of the outer ring can be divided into three stages. In the first stage, the forming distance is 0–1.5 mm, and the forming force is approximately 60 kN. At this stage, the contact part between the outer ring blank and the die will produce large plastic deformation. The dominant forming force is the deformation resistance caused by the plastic deformation of titanium alloy, and the forming force increases rapidly. In the second stage, the forming distance is 1.5–3.5 mm, and the forming force is approximately 60–80 kN. In this stage, the plastic deformation of the contact part between the die and the outer ring is reduced, and the outer ring blank mainly produces bending deformation. The bending resistance caused by the bending deformation of titanium alloy is the main factor in producing the forming force in this stage. The third stage is when the forming distance is more than 3.5 mm. In this stage, the outer ring produces a large bending deformation. The inner liner of the outer ring contacts the bearing inner ring. The blank of the outer ring is extruded by the die and the bearing inner ring, resulting in large extrusion deformation resistance. This is the main factor of the forming force in this stage, and the forming force rises sharply.

The difference $\Delta R$ between the track radius of each point on the inner surface of the outer ring after forming and the target radius in the test and simulation is shown in Fig. 17.

$$\Delta R = R_i - R_j$$

where $R_i$ is the track radius of each point on the inner surface of the outer ring after forming, $i = 1, 2, 20$, and $R_j$ is the target radius.

It can be seen from the figure that the track radius of the simulation is similar to that of the test, which proves that the simulation accuracy is good. After forming, the two ends of the outer ring are not symmetrical about the middle, which may be related to the change in the height and size of the outer ring during the two forming processes. It can be improved by adjusting the two forming distances. The track radius of the inner surface of the outer ring is slightly smaller than the ideal radius, which makes the gasket subject to certain extrusion deformation and ensures the no-load rotational breakaway torque of the bearing. After the bearing is formed, it also needs to be machined. After machining (2–10 mm), the extrusion deformation of the gasket is between 0 and 0.2 mm.
Conclusions

To prepare titanium alloy outer ring self-lubricating spherical plain bearings, a two-step extrusion forming process was proposed, and a finite element simulation model of the forming process was established. Furthermore, the influence of the forming process parameters on the forming results was analyzed, and a forming test of titanium alloy outer ring self-lubricating spherical plain bearings was carried out. The main conclusions are as follows:

1. The new process can realize the forming of titanium alloy outer ring self-lubricating spherical plain bearings. The factors affecting the forming results mainly include the die structure, outer ring blank size, and lubrication conditions. The influence on the forming accuracy is forming distance > outer ring blank thickness > friction coefficient > inner surface diameter > die angle. The influence on forming pressure is as follows: the blank thickness of outer ring > die angle > forming distance > friction coefficient > inner surface diameter. Taking GE15DE1TK titanium alloy self-lubricating spherical plain bearing as an example, its forming parameter is determined as outer diameter 30 mm, inner diameter 24.4 mm, height 12 mm, die angle 70°, and forming distance 4.1 mm.

2. A large forming distance easily produces over extrusion defects, while a small forming distance easily produces insufficient extrusion defects. It needs to be adjusted with other process parameters. The excessive thickness of the outer ring blank will reduce the bending capacity of the blank, produce the effect of upsetting, and increase the forming pressure. On the premise of ensuring machining allowance, the thickness of the outer ring blank should be reduced as much as possible. The large friction coefficient under the new process does not necessarily have a negative impact on the forming accuracy. To improve the service life of the die, the lubrication conditions should be improved as much as possible.

3. The forming pressure can be divided into three stages. The new process can control the extrusion amount of the gasket by optimizing the forming process parameters and can directly prepare the self-lubricating articulated bearing that meets the standard requirements of no-load rotational breakaway torque without adjusting through subsequent processes.

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Author contribution Song Zhao: Conceptualization, data curation, formal analysis, investigation, methodology, visualization, and writing—original draft; Xiao Yang: writing—review and editing, methodology, formal analysis, and data curation; Changxin Liu: software and conceptualization; Abderrahim Ezzaid: writing—editing and investigation; Bingli Fan: funding acquisition and project administration; An Nan Sun: visualization and validation; Heng Wang: funding acquisition and resources; Xiaowen Qi: funding acquisition, conceptualization, supervision, writing—review and editing, and project administration.

Funding This study was supported by the Ministry of Education’s Industry University Cooperation Collaborative Education Project Fund (grant no. 202102009003).

Declarations

Competing interests The authors declare no competing interests.

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