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**V-shaped bending of Ti-6Al-4V titanium alloy sheet with elliptical hole**

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**Abstract**

The internal elliptical hole defect in the Ti-6Al-4V titanium alloy sheet strongly affects the material mechanical properties during the bending process. In this study, the finite element method (FEM) is used to study the effect of internal hole on mechanical properties of the sheet subjected to the V-shaped bending. The fracture damage, the equivalent strain and the principal stress in the sheet with elliptical hole (the defect sheet) and the hole-free sheet (the perfect sheet) are analyzed contrastively under different punch speeds and radii. The results show that the load in the defect sheet and the perfect sheet has different trends during the bending process. Compared to the perfect sheet, both the damage and the equivalent strain in the defect sheet obviously increase, and the distribution of the principal stress in the bending zone of the defect sheet has a significant change. The hole causes the different evolution of the maximum damage, the equivalent strain, and the maximum tensile and compressive stresses with the increase of punch speed and radius for the defect and perfect sheets. The current results serve a feasible approach to predicting the fracture of the sheet with internal hole during the V-shaped bending process, and provide a guidance for the V-bending experiments of the defect and perfect sheets in the subsequent work.

**1. Introduction**

Sheet metal forming has been widely used in daily life, which played an important role in various industries. But there are still some problems in sheet metal forming process due to a lack of knowledge in considering the efficient use of material and energy [1]. Titanium and its alloys have got a better development since the excellent properties were found gradually [2], and they were applied in aerospace industry owing to their high strength to weight ratio and excellent corrosion resistance [3]. The pure titanium has been a potential material for structural components and attracted much attention from the electronic industry recently due to its lightweight and high specific strength [4]. In order to obtain a better performance of the sheet materials in service process, it is essential to analyze the sheet metal forming process [5].

Because the spring-back phenomenon and fracture are major failure modes in the bending process, a lot of researchers applied themselves to improve performance in this field. The effects of punch radius, material strength, and sheet thickness on the springback angle are experimentally tested to determine the dominant parameters for reducing the springback angle in the sheet bending process for high-strength steel sheets [6]. The ability and behavior of titanium alloy in the stretch-drawing process are investigated in detail [7]. The effects of lubrication, material properties, and process geometries on deviation in the bending point were experimentally tested to identify the main parameters of position deviation in sheet metal bending processes [8]. The effects of the punch radius on the spring-back phenomenon considering different sheet of aluminum/polypropylene was analyzed in the early stage [9]. Zhang et al [10] applied experimental method to study V-shaped sheet forming mechanisms through deformable punches and rigid dies. The phenomenon of spring-back and spring-go was
In the current work, the FEM is utilized to simulate the three-dimensional V-shaped deformation process of the stainless steel was analyzed. The characteristics of the spring-back between the asymmetrical and symmetrical U-bending process was clearly compared based on FEM [12]. Thipprakmas et al [13] and Kuo et al [14] clarified that the effects of process parameters and optimized the results of sheet V-bending process in association with the Taguchi method and the analysis of variance (ANOVA) techniques. Huang [15] analyzed a V-die coining process through elastic-plastic FEM in bending sheet metal. Wang et al [16] presented a mathematical model for metal sheet forming used plane-strain theory.

Thipprakmas et al [17] illustrated that the punch stroke under the different punch speed and radius strongly affected the bending forces of air bending process by the spring-back response method. Thipprakmas [18] performed a FE analysis of effects of punch height on the bending angle applied the material flow analysis and stress distribution analysis. Phanitwong et al [19] investigated the effects of part geometry on the spring-back/spring-go feature using the FEM simulation and validated through laboratory experiments. Duc-Toan et al [20] used the modified Johnson-Cook model and considered the effects of the temperature to predict the springback of magnesium alloy in V-bending process. Thipprakmas [21] predicted the mechanism of V-bending process using the FEM simulation and proposed a means of the sided coined to control the spring-back and spring-go. Ma et al [22] identified the ratio of the thickness with grain size of metal foils have a relationship with the springback behavior. Nakamachi et al [23] investigated the bendability and springback evolution using the two-scale FE model based on crystallographic homogenization method.

Besides the phenomenon of springback often occurred in the metal sheet forming process, the internal defects contained in the metal material also strongly affect the quality of metal forming. Chen [24] analyzed the plastic deformation of porous metal sheets with void defects and investigated the void closure behavior, the distribution of relative density and stress-strain for various roll conditions. Chen et al [25] and Wang et al [26] described the evolution of the internal void defects with respect to the large deformation and high temperature during the hot forming process. Chen et al [27] used the FEM to predict the degree of void defects in cold rolling process and developed a comprehensive procedure to improve the material performances. Li et al [28] revealed the mechanism of crack healing at room temperature in terms of the atomic diffusion and the dislocation shielding through the molecular dynamics simulation. Recently, the important contributions related to the nanoscale machining induced the stress area and the subsurface damage on ductile and brittle materials has been investigated by Li et al in detail and thoroughly [29, 30], considering the machining speed, depth of cut, tool tip radius, crystal orientation and defect effect during the machining process. Hence, it is necessary to study the effect of the hole defects at the macro level during the bending process.

Previous work was carried out, based on the assumption that metal sheet forming without the defects. In fact, it is inevitable to lead to the presence of holes and cracks in the material in the manufacturing process of the raw material, due to the shrinkage and gas evolution during solidification [27]. Therefore, the hole defects in the materials should be considered to improve the accuracy and quality of the metal sheet forming process [24, 25]. However, the effect of hole on the V-shaped bending process is still unsolved, which limits the improvement of material properties. In the current work, the effects of the hole in the bending zone on the V-shaped bending process are investigated, in term of the damage, the equivalent strain and the principal stress by FEM simulation.

In addition, the parameters have a significant influence on the sheet bending process. Especially, the punch speed and radius play an important role during the bending process and are widely studied in previous work. Kim et al [31] investigated the spring-back characteristics of V-shaped forming process under the different punch speeds. Ma et al [32] illustrated that the punch speed changed the strain state of sheet metal forming and affected the forming limit of material, thereby making the material to exhibit different hardening characteristics. In addition, Parsa et al [9] presented the relationship between the contact condition and the punch radii, which affects the contact pressure, the stress distribution and the spring-back angle in the V-die bending process. Huang and Leu [33] clarified the effects of the punch radii on the load-stroke characteristic and the bend angle of the bending part after unloading of the V-die bending. That the large or small punch radius leads to the difference in the contact condition also has been demonstrated in the previous work [34].

Therefore, the effects of hole on the V-shaped bending process is studied based on the FEM simulation method under the punch radius of 1.5 mm, the bending angle of 120°, and the punch speeds of 0.5, 0.8, 1.0, 1.5 m s⁻¹ [35], respectively. Furthermore, the same method is applied to analyze the effects of hole on the V-shaped bending process with respect to the different radii under the punch speed of 1 ms⁻¹, the bending angle of 120°, and the punch radii of 1.0, 1.5 and 2.0 mm [13, 34], respectively.

2. Finite element model

In the current work, the FEM is utilized to simulate the three dimensional (3D) model of the V-shaped bending process by commercial software DEFORM-3D [36, 37]. According to the previous work [35, 38], the FE models
of V-shaped bending simulation are built by the 3D modeling software of Pro/E, and then are imported the DEFORM-3D, as shown in figure 1. The length, width and thickness of the bending sheet are 90 mm, 90 mm, and 1.5 mm, respectively. The die radius is 3 mm, and the bending angle is 120°. The contact between die and sheet is stress-free before V-shaped bending, and the geometric parameters of die, sheet, and die are presented in figure 1 and table 1. In order to save the calculated time, the rigid punch and die are used in FEM simulation process. The triangular mesh is used, and the ambient temperature of 20 °C is set [39]. Based on the previous experiments and simulations [13, 34, 35], the different punch speeds of 0.5, 0.8, 1.0 and 1.5 m s⁻¹ and punch radii of 1, 1.5, 2 mm are set to study the effect of the punch speed and radius on the V-bending of defect sheet. The die is restrained by the encastre. The friction conditions are set in the punch-sheet and die-sheet interfaces using a friction coefficient of 0.3 [34, 40]. When the sheet is pressed by the punch with a constant speed, the plastic shear friction occurs between the sheet and the die. The detail geometrical parameters of the V-shaped bending simulation are summarized in table 1.

3. Materials

The workpiece material of Ti-6Al-4V titanium alloy is set as an elastic-plastic type, and has high strength and good stamping performance as well as good resistance to brittle fracture performance. The material properties, including elastic modulus, tensile strength, poisson ratio, and material density of Ti-6Al-4V titanium alloy used in this simulation are based on the database in DEFORM-3D [36]. The V-shaped bending deformation process is controlled by the material properties. The elastic modulus and poisson ratio decides the elastic deformation. According to previous work [41, 42], the tensile strength instead of true stress-strain curve of Ti-6Al-4V titanium alloy is used to control the plastic behavior in the current FEM simulations. The detail parameters of material properties are shown in table 2.
Through the FEM simulation, the effects of hole defects in the bending area on the V-shaped bending of titanium alloy sheet at room temperature (20°) are studied. The different punch speeds and radii are used in the FEM simulation to analyze the effect of punch speed and radius on the damage, the equivalent strain and the principal stress. Here, the damage criterion of the Cockcroft & Latham is used, which is shown in equation (1).

\[ C = \int_0^{\varepsilon_f} \frac{\sigma_*}{\bar{\sigma}} d\varepsilon \]  

where \( \sigma_* \) is the maximum principle stress, \( \varepsilon \) the equivalent strain, \( \varepsilon_f \) the equivalent strain at which the fracture occurs, \( C \) the material constant to express the limit of ductile damage.

In the FEM simulation, a hole is assumed inside the workpiece. Because the bending process is geometric symmetrical, one half of the sheet is used to easily observe the evolution process of hole defects in the FEM simulation. The mesh of the sheet with a hole is shown in figure 2.

### 4. Results and discussion

#### 4.1. Load-stroke characteristics

The load-stroke curves of the bending process based on the FEM simulation are shown in figure 3. The black line is the load-stroke curve of the hole sheet, and the red line represents the load-stroke curve of the perfect sheet. The trend of the load-stroke curve is that the load first increases and then decreases slowly, afterwards with a rapidly rise near the end of the punch stroke with increasing the punch stroke. The load-stroke curves can be divided into three deformation stages, including the elastic deformation stage, the plastic expansion stage and the coining stage. With the increase of punch stroke, a linear trend of the load-stroke curves shows the elastic deformation stage, and the plastic expansion stage shows that the load first increases and then decreases, and finally drops down to the minimum value of the process showing. The coining stage shows that the load rises

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**Table 2. Material properties.**

| Elastic modulus (Gpa) | Tensile strength (Mpa) | Poisson ratio | Material density (g cm⁻³) |
|-----------------------|------------------------|--------------|--------------------------|
| 117.211               | 1350                   | 0.3          | 4.5                      |

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**Figure 2.** Global and local enlargement of the sheet mesh distribution.

**Figure 3.** Load-stroke curves of the hole sheet and the perfect sheet.

**Table 2.** Material properties.
sharply in the end of punch stroke. The point of the minimum value in load is the demarcation point between the plastic expansion stage and the coining stage. The evolution trend of load-stroke curves is consistent with those obtained by Zhang et al [10] and Kim et al [31] based on the bending experiments.

In addition, figure 3 shows a comparative analysis of the load-stroke curves of the hole sheet and the perfect sheet under the same loading conditions. The results indicate that the stroke in elastic deformation stage of the hole sheet is shorter than that of the perfect sheet. The load in the hole sheet is first larger than that in the perfect sheet in the elastic stage, and then less than that in the perfect sheet in the plastic expansion stage. This phenomenon means the hole in the bending area affects the spread of deformation energy when the sheet is forming. The load in both the hole sheet and the perfect sheet rises sharply in the coining stage due to the fact that the sheet contacts sufficiently with the punch.

In addition, the punch speed and radius, as two main parameters affecting the V-shaped bending process, are studied in the current work. Figure 4 shows the effects of the punch speed and radius on the load-stroke curves with respect to the hole sheet. Figure 4(a) indicates that during the elastic deformation stage, the bending load increases with the punch speed increase at the same stroke and punch radius. However, there is a little difference in bending load under the different punch radii at the same stroke and punch speed, as shown in figure 4(b). The similar results also is found in the work of Leu, based on the FEM and experiment methods [8].

4.2. Effect of elliptical hole
Hole defects in the materials strongly affect the performance of products and shorten its service time [25]. Hence, it is essential to analyze the effects of hole defects on the forming process of metal sheet. In this paper, the state change of microscopic holes can be observed indirectly from the FEM simulation. The effects of hole on the bending process of sheet can be analyzed by considering the strain and stress distributions, and the damage change in V-shaped bending process. The simulation follows these conditions: the punch speed is 1 ms\(^{-1}\), the sheet thickness 1.5 mm, the punch radius \(R_p = 1.5\) mm, and the bending angle 120°.

Figure 5 presents a striking contrast of simulation results between the hole sheet and the perfect sheet, including the damage, the equivalent strain and the principal stress contours which are symmetric distribution in the V-shaped bending process. The damage, the equivalent strain and the principal stress on the outside of the bending region are significantly greater than those on the inner side of the bending region, meaning that the damage and deformation behavior on the outside of the bending region is larger than those on the inner side of the bending region. The similar phenomenon also is found during the hot v-bending of Ti-6Al-4V alloy sheets [34]. Moreover, figure 5(a) shows that compared with the perfect sheet, the damage value in the bending zone is elevated owing to the hole in the defect sheet. This indicates that the hole makes the damage easy to occur in bending region during the V-shaped bending of sheet. Figure 5(b) shows the distribution of equivalent strain to reflect the deformation behavior of workpiece material during the bending process. It can be observed that the large equivalent strain only emerges on the inner side and outside of the bending region in perfect sheet, but around the hole defect in the bending region of hole sheet. This is because the hole defect in the sheet changes the material flow when the sheet is formed. In addition, it is worth pointing out that the equivalent strain distribution agrees well with the corresponding result induced by the V-bending of Ti-6Al-4V titanium alloy sheets via ABAQUS simulation [34], further illustrating the rationality of current simulations. Figure 5(c) shows the distribution of the principal stress in the sheet subjected to the V-bending. This is also consistent with the
result revealed by Zong et al [34]. The principal stress is negative on the inner side of the bending region, showing that the region bears the compressive stress. And the principal stress is positive outside of the bending region that means the region withstands tensile stress. Based on the fact that the contact region withstands compressive stress and the non-contact zone withstands the tensile stress, the contact state of the sheet with the punch is obtained from principal stress distribution during the bending process. In addition, the compressive stress in bending region of the hole sheet existed below the punch tip is far larger than that of the perfect sheet. The tensile stress of the hole sheet is also larger than that of the perfect sheet outside of bending region. Moreover, according to the previous work [13], the spring-go phenomenon occurs after unloading due to the distribution of principal stress and it can be predicted that the spring-go angle in hole sheet will be bigger than that in the perfect sheet. These results confirm that the hole defect in sheet leads to the differences in the damage degree, the material flow and the spring-go phenomenon during the V-shaped bending process.

Figure 5. Comparison of the perfect sheet (left) and the hole sheet (right): (a) damage distribution, (b) equivalent strain distribution, (c) principal stress distribution.
4.3. Effect of punch speed

Figure 6 shows the distribution of damage in the hole sheet at different punch speeds. The damage value increases with the punch speed increase. The distribution of damage is consistent with that of the tensile stress roughly in the bending zone. Figures 7(a) and (b) show the evolution of damage value for the hole sheet and the perfect sheet with the increasing punch stroke, respectively. The results indicate that the damage value of the hole sheet rise gradually as the punch speeds increase at the same punch stroke, but that of the perfect sheet has little change. Figure 7(c) and table 3 show that the maximum damage value of hole sheet is larger than that of perfect sheet during the V-shape bending. Moreover, the maximum damage value of the hole sheet increases with the increasing punch speed, but that of the perfect sheet increases after an initial decrease.

Figure 8 shows the equivalent strain distribution of the hole sheet at different punch speeds. The equivalent strain in sheet in contact with the sides of the punch is larger than that with the tip of the punch, and the equivalent strain at the surroundings of the hole defects is very small. This is because a large surface energy in hole boundary acts as a barrier to the material flow. In addition, it can be observed that the equivalent strain and its distribution zone increase with the increase of the punch speed. Figures 9(a) and (b) show the evolution of the equivalent strain in the hole sheet and the perfect sheet with the punch stroke increase. The results indicate that
the equivalent strain increases with increasing punch speed in the hole sheet, but has a little change in the perfect sheet. Table 4 and Figure 9(c) show the maximum equivalent strain in the hole sheet with the perfect sheet at different punch speeds. The maximum equivalent strain increases as the punch speed increases in the hole sheet, but first declines and then rises in the perfect sheet. These results demonstrate that during the bending process, the hole defect in the sheet changes the material flow in the hole surroundings from the equivalent strain distribution.

Figure 10 shows the distribution of principal stress in the hole sheet at different punch speeds. The tensile or compressive principal stress is determined by the contact situation. The compressive stress emerges in the...
contact zone roughly, but the tensile stress in non-contact zone. It can be seen from figure 10 that the principal stress increases with the increasing punch speed in same position of sheet. According to the analysis results by Thipprakmas et al [13], the spring-go phenomenon could occur after unloading based on the principal stress distribution and become obvious with the increasing punch speed. Figures 11(a) and (b) show the evolution of the principal stress in the hole sheet and the perfect sheet, respectively. The symbol of asterisk (*) in the two graphs represents the compressive stress curves. The results indicate that the principal stress in the hole sheet increases with the punch speeds at the same punch stroke. In the perfect sheet, the evolution of principal stress is

| Punch speed (ms⁻¹) | 0.5 | 0.8 | 1.0 | 1.5 |
|-------------------|-----|-----|-----|-----|
| Maximum equivalent strain of hole sheet (%) | 0.61 | 0.84 | 1.06 | 1.84 |
| Maximum equivalent strain of perfect sheet | 0.5 | 0.49 | 0.48 | 0.67 |
similar to that in the hole sheet, but the value is smaller than that in the hole sheet during the bending process. Table 5 and figure 11(c) present that the maximum tensile stress increases and the maximum compressive stress decreases with the increasing punch speed in the hole sheet, but in the perfect sheet, the maximum principle stress has a little change when the punch speed increases. The results indicate that the hole defects make the bending stress of sheet increased during the bending process.

### 4.4. Effect of punch radius

Figure 12 shows the distribution of the hole sheet damage at different punch radii. It can be seen that the damage in same position decreases gradually but the damage zone becomes larger from figures 12(a)–(c). In addition, the sheet surface on the inner side of the bending zone becomes smooth with the increase of punch radius, and the obvious coining appears on the inner side surface under the punch radius of $R_p = 1.0$ mm. It is obtained from table 6 and figure 13 that the maximum damage of the hole sheet is larger significantly than that of the perfect sheet, and the maximum damage of both the hole sheet and the perfect sheet decreases with the increasing punch radius.

#### Table 5. Maximum and minimum stress of the hole sheet and the perfect sheet.

| Punch speed (ms$^{-1}$) | 0.5 | 0.8 | 1.0 | 1.5 |
|-------------------------|-----|-----|-----|-----|
| Maximum stress in the hole sheet (MPa) | 1782 | 1870 | 1929 | 2164 |
| Maximum stress in the perfect sheet | 1811 | 1840 | 1840 | 1929 |
| Minimum stress in the hole sheet | $-1340$ | $-1428$ | $-1546$ | $-1634$ |
| Minimum stress in the perfect sheet | $-1929$ | $-1900$ | $-1940$ | $-1870$ |

#### Table 6. Maximum damage of the hole sheet and the perfect sheet at different punch radii.

| Punch radius (mm) | 1.0 | 1.5 | 2.0 |
|-------------------|-----|-----|-----|
| Damage of defect sheet | 0.85 | 0.71 | 0.62 |
| Damage of perfect sheet | 0.61 | 0.47 | 0.43 |

Figure 12. Damage distribution in the hole sheet at different punch radii: (a) $R_p = 1.0$ mm, (b) $R_p = 1.5$ mm, (c) $R_p = 2.0$ mm.

Figure 13. Evolution of maximum damage versus the punch radius.
radii. The results also reveal that the small punch radii could cause fracture outside of bending region when the sheet stamped.

Figure 14 presents the effects of punch radii on the V-bending of sheet by comparing the equivalent strains at different punch radii. It can be observed from figures 14(a)–(c) that the larger equivalent strain is gradually away from the bending zone. This is because with the increasing punch radii, the distance from the contact point between the sheet with the punch sides to that with the punch tip becomes larger, and the contact state strongly affects the material flow during the bending process. Table 7 and figure 15 present that the maximum equivalent strain in the hole sheet is larger than that in the perfect sheet, and those in the hole and perfect sheets decrease with the increasing punch radius.

Figure 16 shows the distribution of principal stress in the hole sheet at different punch radii. It is clear from figures 16(a)–(c) that both the distribution zone of the compressive stress on the inner side of bending region and that of the tensile stress on the outside of bending region become larger with the increasing punch radius. Based on the analysis of stress state by Thipprakmas et al [13], the spring-go phenomenon could occur after unloading due to the distribution of principal stress. As the punch radius increases, this phenomenon will become inconspicuous and even turn into spring-back phenomenon. Table 8 and figure 17 shows the evolution of the maximum principal stress in the hole and perfect sheets at different punch radii. The tensile stress in the hole sheet is larger than that in the perfect sheet whereas the compressive stress in the hole sheet is smaller than that in the perfect sheet. As the punch radius increases, the maximum tensile stress and the maximum compressive stress decrease under the hole sheet. However, in the perfect sheet, the maximum tensile stress

| Punch radius (mm) | 1.0 | 1.5 | 2.0 |
|-------------------|-----|-----|-----|
| Equivalent strain of defect sheet (%) | 1.15 | 1.07 | 0.96 |
| Equivalent strain of perfect sheet | 0.83 | 0.47 | 0.4 |

Figure 14. Comparison of equivalent strain distribution in the hole sheet versus the different punch radii: (a) \( R_p = 1.0 \) mm, (b) \( R_p = 1.5 \) mm, (c) \( R_p = 2.0 \) mm.

Figure 15. Evolution of maximum equivalent strain versus the different punch radii.
increases and the maximum compressive stress decreases. The results show the distribution and the value of the principal stress are affected by the punch radius.

5. Conclusions

The effects of the hole defect on the V-shaped bending of titanium alloy sheet are investigated at different punch speeds and radii via the FEM simulation. The changes of the damage and the equivalent strain as well as the principal stress are compared to response the effects of the hole on the bending zone during the bending process. The conclusions are as follows:

(1) The load-stroke curves of the hole sheet and the perfect sheet are obtained according to the FEM simulation. The overall trend in the load-stroke curve is that the load first increases and then decreases slowly, afterwards a significant increase in the final phase of the stroke with increasing the punch stroke. The plastic deformation of hole sheet occurs earlier than that of the perfect sheet. The load in the hole sheet is first larger than that in the perfect sheet in the elastic stage and then less in the plastic expansion stage. Furthermore, the punch speed has a relatively larger influence on the load than the punch radii.
(2) The punch speed significantly affects the V-shaped bending. However, the influence is different under the bending of the hole sheet and the perfect sheet, based on the evolution of the principal stress, the equivalent strain and the damage versus the punch speed. For the hole sheet, the maximum damage, the equivalent strain, and the maximum tensile stress increase, while the maximum compressive stress decreases with the punch speed increase. For the perfect sheet, the maximum damage and equivalent strain first decrease and then increase, and the maximum tensile stress has a little changes while the maximum compressive stress rises with the punch speed increase.

(3) The punch radius also has a greatly influence on the V-shaped bending of the hole sheet and the perfect sheet. The maximum damage and equivalent strain of both the hole sheet and the perfect sheet decrease as the punch radii increase. In addition, both the maximum tensile stress and the maximum compressive stress decrease in the hole sheet with the punch radii increase, whereas the maximum tensile stress increases and the maximum compressive stress decreases in the perfect sheet.

(4) A small punch speed and large punch radius should be selected to induce the small maximum damage and equivalent strain during the V-bending process of Ti-6Al-4V titanium alloy sheet with elliptical hole. Furthermore, no fracture and crack occur in the zone of hole defect, and the closure behavior of the hole defects also has not happened. In addition, incorporating the optimization techniques, such as Taguchi method and analysis of variance techniques mentioned in the above contents, is to optimize the V-bending process in the future. The V-bending experiments of the defect and perfect sheets would also be conducted in the subsequent work to illustrate the effects of hole to the V-bending of sheet experimentally, with the aid of the current FEM simulation results.

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Conflicts of interest

There are no conflicts to declare.

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