



Forming limits and interface damage behavior of different acting surfaces on TA2/Q235B composite plate

Zhi-xiong ZHANG^{1,2,3}, Si-mo ZHANG^{1,2,3}, Xiao-lei BAN^{1,2,3}, Xue-xia ZHAO^{1,2,3}, Zhong-kai REN^{1,2,3}, Jian-chao HAN^{1,2,3}, Chang-jiang ZHANG⁴, Peng LIN⁴, Tao WANG^{1,2,3}, Tian-xiang WANG⁵

1. College of Mechanical and Vehicle Engineering, Taiyuan University of Technology, Taiyuan 030024, China;
2. National Key Laboratory of Metal Forming Technology and Heavy Equipment, Taiyuan University of Technology, Taiyuan 030024, China;
3. Engineering Research Center of Advanced Metal Composites Forming Technology and Equipment, Ministry of Education, Taiyuan University of Technology, Taiyuan 030024, China;
4. College of Materials Science and Engineering, Taiyuan University of Technology, Taiyuan 030024, China;
5. Shanxi Taigang Stainless Steel Precision Strip Co., Ltd., Taiyuan 030006, China

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Abstract: The Nakazima method was applied to performing bulging experiments of annealed TA2 pure titanium/Q235B carbon steel composite plate samples with different sizes. The effects of acting surfaces on forming limits and interface damage behavior of TA2/Q235B composite plate were investigated. It is found that when the steel contacts with the concave die, the bulging height and forming limit of the composite plate increase due to the different contact materials, coordination deformation ability of the interface, and strain state. The bulging height of the R140 specimen reaches the maximum value (46.17 mm), and the thickness reduction and interfacial crack of the R60 and R180 specimens in three directions are larger. In addition, due to the difference in hardness and tensile stress, all horizontal and inclined holes in both groups extend toward the pure titanium.

Key words: TA2/Q235B composite plate; bulging behavior; forming limit; acting surface; interface damage behavior

1 Introduction

Titanium is a superior lightweight material with low density, high strength, and high corrosion resistance [1,2], but high cost limits its large-scale application. Steel has excellent mechanical properties and forming characteristics, and relatively low cost, but its corrosion resistance is far less than that of titanium in environments such as saltwater rich in chloride ions [3,4]. Due to the excellent comprehensive characteristics of the two materials and low utilization of high-value metals, titanium/

steel composite plate is widely used in petroleum, chemical industry, aviation, marine, and other fields [5–9].

In industrial production, deep drawing, bending, stamping, and other processes are often used to produce metal parts [10–15]. Stamping technology is one of the main methods of plastic processing of sheet metal with the advantages of high production efficiency, good product quality, and high utilization rate of material. Thin-walled titanium/steel composite parts prepared by stamping procedure are mainly used in pressure-resistant housing, heat exchangers, condensers, and various

Corresponding author: Zhi-xiong ZHANG, Tel: +86-19834438583, E-mail: zhangzhixiong@tyut.edu.cn;
Xue-xia ZHAO, Tel: +86-13994224626, E-mail: xuexiazhao@126.com

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chemical reaction vessels on board ships [16–18].

Bulging is a basic form of stamping deformation, and its principle is to use the power provided by the convex die to gradually thin the sheet to obtain parts with special geometry. The main purpose of the bulging test is to determine the forming limit diagram (FLD) [19–24] and realize the maximum forming capacity of the sheet and identify the damaged areas. The bulging behavior of metal plates has been widely studied. LIU and GUO [25] analyzed the effect of the heat treatment process and acting surfaces on the forming limit of copper–aluminum laminate by bulging experiment. It was shown that the forming limit of the laminate is higher when copper is on the outside, and the heat treatment process plays an important role in improving the forming limit. The fracture of the metal on both sides of the laminate is accompanied by partial detachment of the interface. YOSHIDA and HINO [26] proposed a localized necking criterion for laminates, calculated the forming limit of stainless steel–aluminum laminates, and analyzed the effect of pre-strain on forming performance. YAN et al [27] obtained the forming limit diagrams of 0.5 and 0.8 mm TA2 pure titanium sheets using Nakazima experimental method. The results showed that the forming limit of TA2 pure titanium plate reaches the lowest value at plane strain state, and reaches the highest value at uniaxial strain state. They predicted the forming limit of TA2 pure titanium plate by the improved Hill48 yield criterion. XIE and YUAN [28] studied the bulging behavior of thin-walled welded low-carbon steel tubes (STKM11A). They found that the fracture pressure, the thickness reduction, and the ultimate expansion ratio of the tubes decreased with the increase of the bulging area, and the contour of the bulging zone gradually deviated from the ellipse sharp when the aspect ratio reached 2.0. Moreover, they established the forming limit diagram of welded STKM11A steel based on the transformation of the stress state.

Obviously, besides the plastic deformation ability of pure titanium and carbon steel, the bonding strength and the coordination deformation

ability of the interface of laminate also directly affect the plastic forming performance, which is closely related to the stamping process. At present, the forming properties of titanium/steel composite plate and their stamping process have not been studied in depth, and the prediction of the fracture position of composite plates at different strain states and the influence mechanisms of different acting surfaces on the forming limit are not clear.

In the present work, the bulging deformation of annealed TA2/Q235B composite plate by the Nakazima method at room temperature was analyzed and the deformation ability of the plates was investigated when the pure titanium and the carbon steel were in contact with the concave die, respectively. The causes of the fracture position of the composite plate at different strain states and the influence of different acting surfaces on the formability were analyzed. This study is expected to obtain the size and location of the fracture during the bulging process to improve the quality of parts and ensure the stability of mass production.

2 Experimental

2.1 Materials

The titanium/steel composite plates used in this experiment were produced by Xi'an Tianli Clad Metal Materials Co., Ltd. (China). The original TA2/Q235B composite plate was prepared by the explosion–rolling process. Before the explosion, the pure titanium (6 mm) was used as cladding plate, and the carbon steel (23 mm) was used as the substrate. After rolling at 830 °C and annealing at 545 °C for 2 h, the ultimate thickness of pure titanium is reduced to 1 mm and that of the carbon steel is reduced to 3 mm. The chemical composition of the original material is given in Table 1. The shape of the “dog bone” sample recommended in ISO-12004-2—2008 standard was fine-tuned for the bulging experiment, and the adjusted geometry is shown in Fig. 1. The edges of samples were polished with sandpaper to avoid the stress concentration. The sample sizes were designed for 10 different Rn values, as given in Table 2.

Table 1 Chemical composition of TA2/Q235B composite plate (wt.%)

Material	Fe	Ti	C	Si	Mn	P	S	N	H	O
TA2	0.18	Bal.	0.06	—	—	—	—	0.01	0.01	0.17
Q235B	Bal.	—	0.18	0.33	0.92	0.0015	0.0015	—	—	—

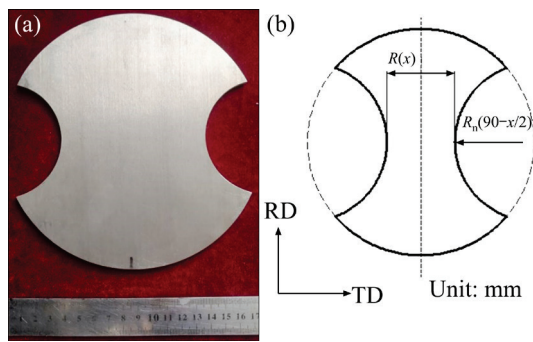


Fig. 1 Specimen before bulging (a) and dimensions of bulging specimens (b)

Table 2 Dimensions of bulging specimens

Strain state	R/mm	R_n/mm
Uniaxial	20	80
	40	70
	60	60
	80	50
Plane	90	45
	100	40
	120	30
	140	20
	160	10
	180	0

The bulging experiments were divided into Group A and Group B according to the acting surfaces of the composite plate. The contact between pure titanium and the concave die was recorded as Group A, and the contact between carbon steel and the concave die was recorded as Group B.

2.2 Forming limit test

The Nakazima method (hemispherical rigid

punch bulging experiment method) was applied to the bulging experiment on the Jinbang EC600 sheet-forming experimental machine designed according to the national standard GB/T 15825.3—2008. The diameter of the semi-spherical punch was 100 mm, and the stamping speed was set to be 0.5 mm/s. Before the experiment, the solid-liquid mixed lubrication of polytetrafluoroethylene (PTFE) film and vaseline lubricant were applied uniformly on the sample surface and then followed by spraying with random black and white spots. Different forces were set for the specimens of different sizes, as given in Table 3.

Table 3 Blank holder force of samples with different dimensions

R/mm	20	40	60	80	90	100	120	140	160	180
Force/ kN	65	150	200	230	250	280	330	380	400	450

In this experiment, the edge of a specimen was firmly fixed using a blank holder and then the plate was bulged into a concave die by applying pressure until bursting occurred. The punch speed was set to be 0.5 mm/s. Arimis 2017 controlled the high-speed camera to record the image variation characteristics of black and white spots on the surface of the specimen, and the strain was calculated by the change of the image feature through an image processing technique (Fig. 2). When the plate broke, the experiment was stopped immediately.

2.3 Microstructural characterizations

Samples were taken from the central part of the specimen along the RD and TD directions, respectively. Pure titanium was corroded by Kroll reagent, while carbon steel was corroded by 4% nitric acid alcohol solution. The microstructure near

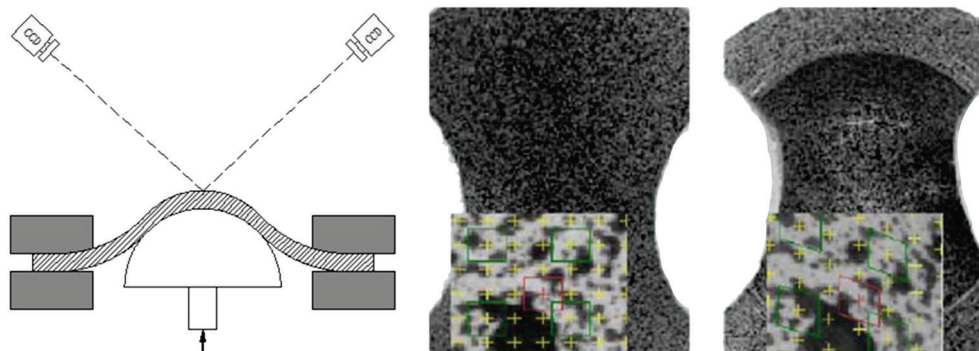


Fig. 2 Strain measurement technology based on machine vision

the bonding interface of the TA2/Q235B composite plate was observed by JSM-IT500 scanning electron microscope.

3 Results

3.1 Forming limit diagram

The bulging experiment results of specimens with different geometries are shown in Fig. 3. It is found that the samples of $R20$ – $R100$ are broken at the center, while the samples from $R120$ to $R180$ are broken at the off-center position.



Fig. 3 Bulging specimens: (a) Group A; (b) Group B

This phenomenon may have two causes: Firstly, the strain states of the specimens $R20$ – $R180$ are different, resulting in different destabilization processes and localized necking conditions of the sheets. From the thickness distribution of bulging parts (Fig. 6), it can be found that at the 90° direction, the $R20$ and $R60$ specimens have abrupt changes in thickness near the center, which is supposed to be concentrative instability. However, $R180$ specimen has a platform area with a gentle thickness change near 16 mm from the center, which is supposed to be diffuse instability. In the subsequent deformation process, the unstable flow of the material is limited to a narrow range of deformation regions and develops into localized instability, and the limiting state of the development of localized instability leads to the rupture of the plate.

Secondly, defects of certain degree may exist in the deformation concentration area of the composite plate. The deformation of the plate increases with the increase of R value, so in the

process of destabilization, the defects in the off-center position fail to bear the load which is broken first.

It is worth mentioning that the location of the fracture does not affect the measurement of the major and minor strains, so it does not affect the accuracy of the forming limit.

The major and minor strains of the samples of different sizes were calculated by Arimis 2017 and plotted into the coordinate system to obtain the scatter plots of FLD. Then the forming limit curves were obtained by quadratic polynomial fitting in MATLAB. The final fitted curves are shown in Fig. 4.

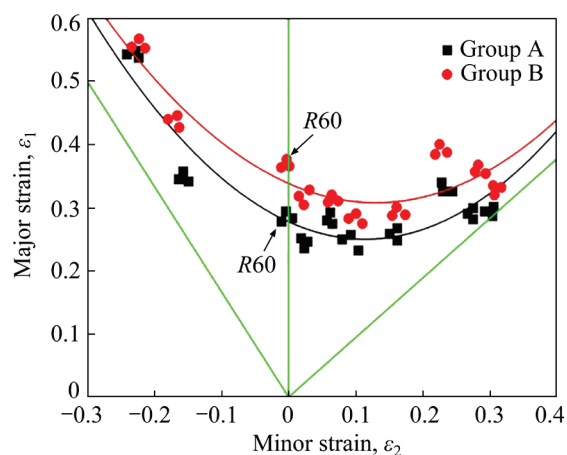


Fig. 4 Forming limit diagram of TA2/Q235B composite plate

The area below the fitting curve is called the safe zone, the points on the curve are in the necking zone, and the points above the curve are in the fracture zone. It is found that the curve of Group A is lower than that of Group B, indicating that when the pure titanium contacts with the concave die, the safe zone is smaller, and the danger zone is larger. This is because the deformation resistance and the surface roughness of pure titanium are both higher than those of carbon steel. Hence, when the pure titanium contacts with the concave die, the friction in the corner area of the die becomes larger, which makes the material flow more difficult. As a result, the punch needs to provide larger forming force in Group A, which leads to the fracture more easily. In addition, due to the zero-point drift phenomenon, the minor strains of $R60$ in both groups are close to 0, so $R60$ is selected as the sample under plane strain state for the macroscopic and microscopic analysis.

3.2 Thickness distribution

Bulging refers to the process in which the sheet gradually becomes thinner under the expansion force. Rupture or necking occurs at the thinnest part of the sheet. Therefore, it is necessary to measure and analyze the thickness change of each position of the sample. In this study, three typical strain states of *R20*, *R60*, and *R180* samples were selected in Group A and Group B for thickness analysis. As shown in Fig. 5, the center of the part was selected as the origin, and the thickness of the plate was measured every 2 mm in the 0° , 45° , and 90° directions relative to the RD, as shown in Fig. 6.

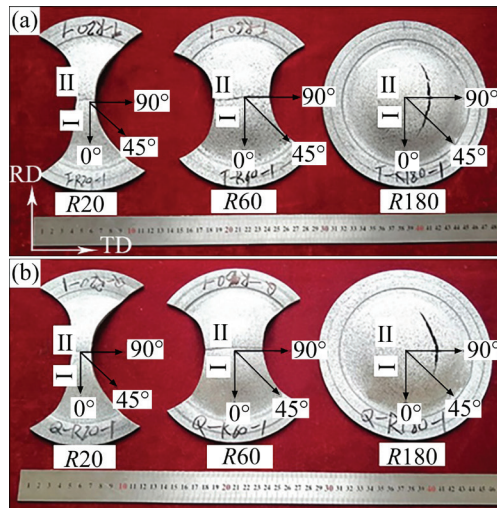


Fig. 5 Samples in TA2/Q235B composite plate bulging parts under three typical strain states: (a) Group A; (b) Group B

As shown in Figs. 6(a, d), the thickness reduction of *R20* specimen in Group A and Group B under uniaxial strain state is basically the same in three directions. The maximum thickness reduction and the minimum average thickness are in the 90° direction. The thickness reduction is smaller and the average thickness is larger in the 0° and 45° directions as compared to those in the 90° direction.

As shown in Fig. 6(e), when the carbon steel contacts with the concave die, the thickness reduction of *R60* specimen at plane strain state is higher than that in Fig. 6(b), but the specimens in both groups have the greatest thickness reduction at 90° direction. The thickness reduction curves of 0° and 45° are similar. In the 45° direction, the thickness of both groups begins to decrease at 43 mm from the center and then begins to increase

again when the distance reaches about 70 mm.

As shown in Fig. 6(f), the thickness reduction of the *R180* specimen at biaxial strain state is greater than that in Fig. 6(c) in three directions. The thickness variation trend of the two specimens in three directions is basically the same, and the thickness reaches the minimum value at 15 mm from the center.

In both groups, the *R20* specimens at uniaxial strain state and the *R60* specimens at plane strain state show the greatest thickness thinning at 90° direction. This is because both *R20* and *R60* specimens are in the necking area with strain concentration where the instability occurs firstly during the forming process. However, the thickness reduction of *R180* in three directions at biaxial strain state is basically the same due to the consistent strain in three directions during the forming process.

As shown in Fig. 6, the thickness reductions of *R20* specimens in Group A and Group B are similar in three directions, while the thickness reductions of *R60* and *R180* specimens in Group B are greater than those in Group A in all three directions, indicating that the plastic forming performance is better when the carbon steel contacts with the concave die. The difference in thickness can be explained by two aspects.

Firstly, the friction coefficient has a significant effect on thickness reduction. When the carbon steel contacts with the concave die, because the deformation resistance and surface roughness of carbon steel are lower than those of pure titanium, the friction and deformation resistance in the corner area of the die is smaller during the bulging experiment, the material flows more easily, the plastic deformation capacity of the plate is stronger, and the plates are not easy to break when they are subjected to larger strains. Therefore, the forming limit and the thickness reduction rate increase.

Secondly, it can be attributed to the difference in the deformation coordination ability of the interface. In the early stage of bulging, the pure titanium plate, carbon steel plate, and interface diffusion layer can coordinate with each other for elastic deformation. However, in the late stage of bulging, the basal laminate undergoes plastic deformation so that the interface diffusion layer cannot coordinate simultaneously, with eventually leads to destabilization and fracture. When the

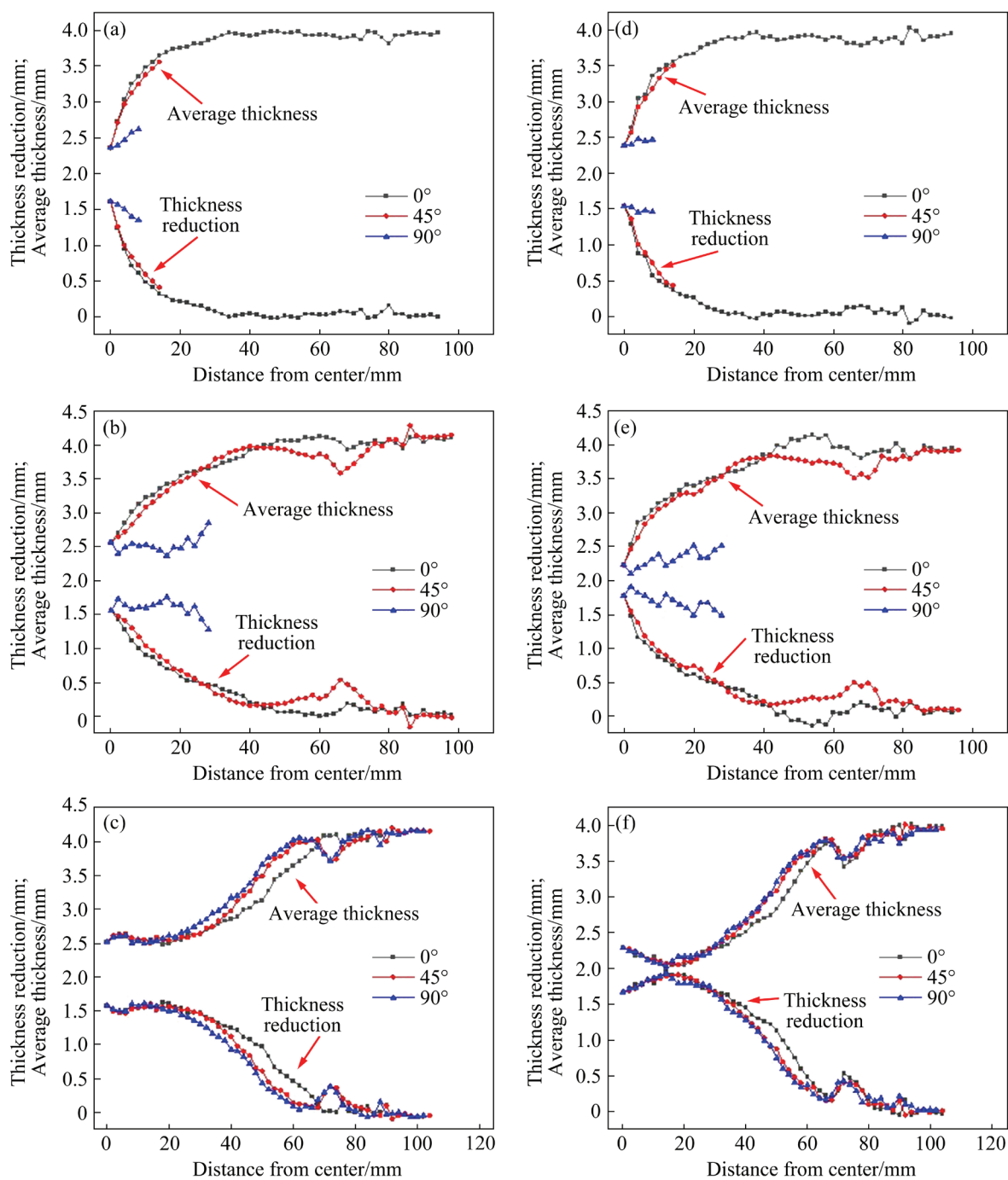


Fig. 6 Thickness distribution in bulging parts of Group A (a–c) and Group B (d–f): (a, d) R20; (b, e) R60; (c, f) R180

carbon steel contacts with the concave die, the interface diffusion layer has a better ability to coordinate the deformation, and the destabilization process of the composite plate is delayed, so the thickness thinning rate is greater.

3.3 Analysis of bulging height

The bulging height is usually used to evaluate the bulging performance of sheet metals. Figure 7 shows the bulging height distribution of Group A

and Group B. The bulging height in both groups reaches the maximum for R140, because the width of the specimens R20–R100 is too small to cover the convex die completely, and the flow of material is limited, resulting in a relatively low bulging height. The curves of the two groups have the same trend, but the values in Group A are generally smaller than those in Group B. It can also be attributed to the influence of friction and the deformation coordination capacity of interface. When

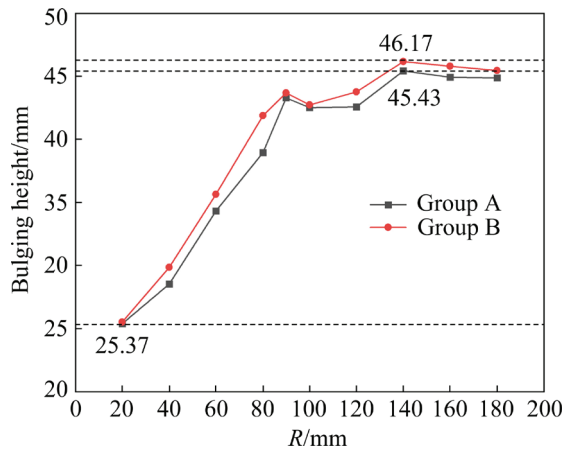


Fig. 7 Bulging height distribution

the carbon steel contacts with concave die, the friction at the corner area of the die is smaller, and the interface diffusion layer has a better ability to coordinate the deformation, so the plastic

deformation capacity of the plate is stronger and less likely to fracture. As a whole, the bulging heights of Groups A and B rise as the R value increases, but there is a slight decrease for $R100$ and $R160$. The values of both groups reach the maximum for $R140$ (Group A: 45.43 mm, and Group B: 46.17 mm), while the value of $R160$ and $R180$ is almost equal and slightly lower than that of $R140$. This is because the edges of the $R160$ and $R180$ specimens are completely covered by the convex die, which makes the material flow more difficultly.

The strain contours of $R80$, $R120$, and $R140$ specimens in Group A and Group B before fracture are shown in Fig. 8. It is found that only one strain concentration band appears in $R80$ and $R120$ specimens, while two bands appear in $R140$ specimens in both groups. Since the $R140$ specimen is completely wrapped around the convex die, the

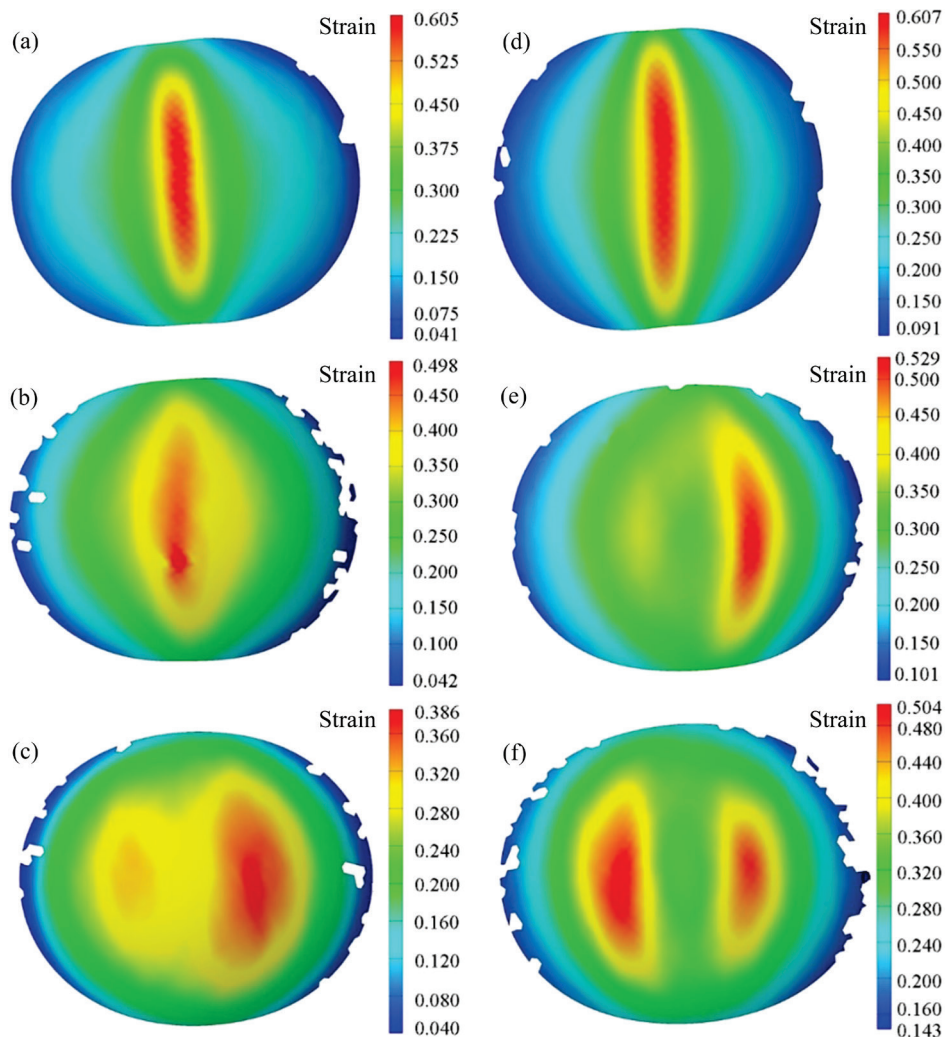


Fig. 8 Strain distribution of different specimens for Group A (a–c) and Group B (d–f) before fracture: (a, d) $R80$; (b, e) $R120$; (c, f) $R140$

punch displacement increases, and the instability region of the plate increases. So, the specimen gets a double peak of strain, which makes the strain of the specimen larger and eventually leads to a higher bulging height.

3.4 Interface microstructure

The interface microstructures of specimens at three typical strain states in Groups A and B are shown in Figs. 9 and 10, respectively, and the specimens were taken at Positions I and II along the RD and TD directions, as shown in Fig. 5.

It is found that three specimens in Groups A and B have different degrees of cracking in the RD and TD directions. The crackings of *R20* specimens in both groups are similar, while the cracking of *R60* and *R180* specimens in Group B is more severe than that in Group A. It is inferred from Fig. 7 that this phenomenon occurs due to the same bulging heights. The bulging heights of *R60* and *R180* in Group B are higher than those in Group A, which means that the plate deformation of the two specimens in Group B is greater.

For the *R20* specimens at uniaxial strain state in two groups, the major strain is larger than 0, and the minor strain is less than 0. Holes extend horizontally towards the pure titanium as seen in Figs. 9(a) and Fig. 10(a), while the holes extend

longitudinally, as shown in in Figs. 9(d) and 10(d).

For the *R60* specimens at plane strain state in two groups, the major strain is larger than 0, and the minor strain is equal to 0, which is the minimum equivalent strain. Vertical holes along the interface are produced, as shown in Fig. 9(b), while horizontal holes are produced toward the pure titanium, as shown in Fig. 9(e). In contrast to Fig. 10(b), both small vertical holes and large horizontal holes are produced toward the pure titanium. In Fig. 10(e), longitudinal crack is found at the interface. When the carbon steel contacts with the concave die, the deformation resistance and surface roughness of carbon steel are lower than those of pure titanium, and there is smaller friction in the corner area of the die, which makes the materials flow more easily and the sheet more prone to deform.

Compared with the *R20* and *R60* specimens, the major and minor strains of the *R180* specimens in two groups at biaxial strain state are larger than 0, which makes the equivalent strain and the plate deformation capacity reach the maximum, so the crack of the *R180* specimens in both groups is more severe than that of *R20* and *R60*. Large inclined holes toward the pure titanium and small vertical holes are produced, as shown in Figs. 9(c) and 10(c), and large vertical holes are produced, as shown in

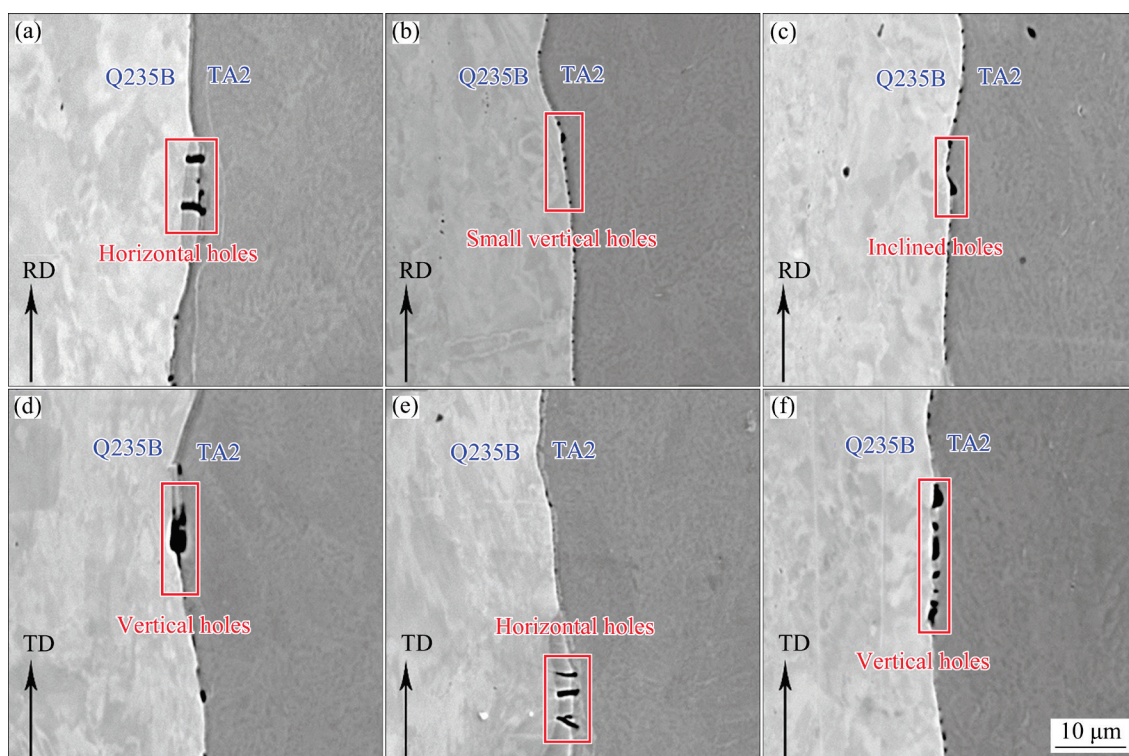


Fig. 9 SEM images of bulging parts of TA2/Q235B composite plate for Group A: (a, d) *R20*; (b, e) *R60*; (c, f) *R180*

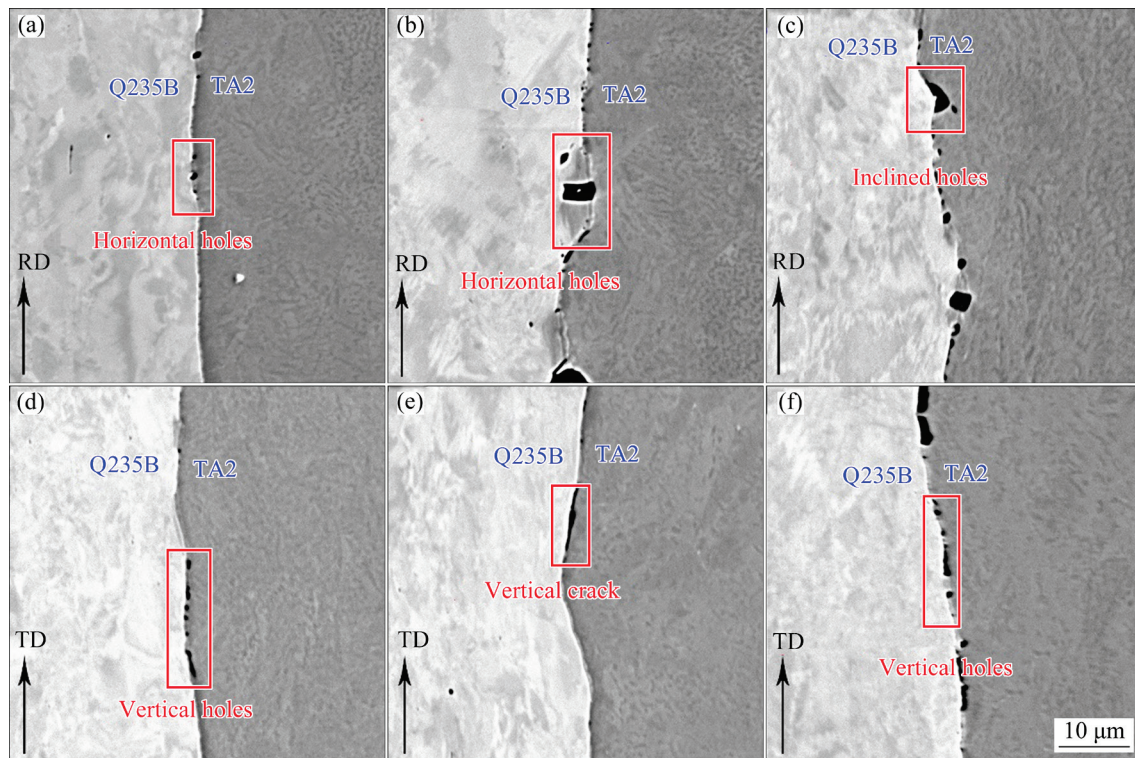


Fig. 10 SEM images of bulging parts of TA2/Q235B composite plate for Group B: (a, d) R20; (b, e) R60; (c, f) R180

Figs. 9(f) and 10(f). The R180 specimens in Group B fracture more severely in both RD and TD directions than in Group A, which is also due to the effects of friction and the coordination deformation ability of interface.

It is found that all the horizontal and inclined holes extend toward the pure titanium. This is caused by the formation of the decarburization layer on the carbon steel side near the interface after annealing and a small number of intermetallic compounds at the bonding interface, which results in the lower microhardness of the decarburization layer than that of the pure titanium, and the holes extend to the pure titanium under high stress in the bulging process.

4 Conclusions

(1) When the carbon steel of the composite plate contacts with the concave die (Group B), the FLD curve is higher than that of the pure titanium (Group A), and the safe zone is enlarged while the danger zone is reduced.

(2) When the carbon steel contacts with the die, the plastic forming performance is better due to the effect of deformation resistance, friction, and

deformation coordination ability of the interface. The bulging heights in Group A are generally lower than those in Group B. The bulging height of both groups reaches the maximum for the R140 specimen (Group A: 45.43 mm, Group B: 46.17 mm), and the thickness reduction of R60 and R180 specimens in Group B is greater than that in Group A in all three directions.

(3) The crack of R20 specimens in the two groups is similar at the RD and TD directions, while the crack of R60 and R180 specimens in Group B is larger than that in Group A. All horizontal and inclined holes extend to the pure titanium, due to the lower micro-hardness of the decarburized layer than that of the pure titanium.

CRediT authorship contribution statement

Zhi-xiong ZHANG: Conceptualization, Methodology, Investigation, Writing – Original draft; **Si-mo ZHANG:** Data curation, Writing – Original draft; **Xiao-lei BAN:** Visualization, Investigation; **Xue-xia ZHAO:** Resources; **Zhong-kai REN:** Software, Validation; **Jian-chao HAN:** Writing – Review & editing; **Chang-jiang ZHANG:** Supervision; **Peng LIN:** Visualization, Validation; **Tao WANG:** Conceptualization, Funding acquisition, Resources, Supervision; **Tian-xiang WANG:** Validation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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TA2/Q235B 复合板不同作用面成形极限及界面损伤行为

张志雄^{1,2,3}, 张斯沫^{1,2,3}, 班晓磊^{1,2,3}, 赵雪霞^{1,2,3}, 任忠凯^{1,2,3},
韩建超^{1,2,3}, 张长江⁴, 林 鹏⁴, 王 涛^{1,2,3}, 王天翔⁵

1. 太原理工大学 机械与运载工程学院, 太原 030024;
2. 太原理工大学 金属成形技术与重型装备全国重点实验室, 太原 030024;
3. 太原理工大学 先进金属复合材料成形技术与装备教育部工程研究中心, 太原 030024;
4. 太原理工大学 材料科学与工程学院, 太原 030024;
5. 山西太钢不锈钢精密带钢有限公司, 太原 030006

摘 要: 采用 Nakazima 实验法对不同尺寸的退火态 TA2/Q235B 复合板样品进行胀形实验, 研究不同作用面对 TA2/Q235B 复合板的成形极限和界面损伤行为的影响。结果表明, 当凹模与碳钢侧接触时, 由于接触材料、界面变形协调能力和应变状态的不同, 复合板的胀形高度和成形极限增加, 其中 R140 试样的极限拱高达到最大值 (46.17 mm), R60 和 R180 试样在 3 个方向上的厚度减薄量和界面裂纹更大。此外, 由于硬度和拉应力不同, 两组样品中所有的水平和斜向孔都向纯钛侧延伸。

关键词: TA2/Q235B 复合板; 胀形行为; 成形极限; 作用面; 界面损伤行为

(Edited by Bing YANG)