Study on the damage behaviour of titanium alloy laser-welded blank during hot gas pressure forming

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Abstract. The damage behaviour of titanium alloy laser-welded seam during hot gas pressure forming was studied by experiment and simulation. The GTN damage model was used to simulate the hot gas pressure forming process of the welded blank. The evolution of the void volume fraction during the forming process was obtained. Hot gas pressure forming experiments of cup-shaped parts were carried out. The microstructure at different positions of the cup-shaped part was observed by scanning electron microscope. Results show that the damage to the weld seam during hot gas pressure forming was mainly related to the strain. The damage of the inside fillet near the flange develops most rapidly, and it easily cracks due to the large deformation during the free bulging stage. The damage on the bottom centre develops slowly at the free bulging stage. After the bottom of the cup-shaped part contacted the die, the volume fraction of damage on the bottom center continued to increase firstly and then reached to a stable value gradually. Various micro cracks were observed during the hot gas pressure forming. The volume fraction of cracks increased with the increasing strain, and the small cracks gradually grew, expanded, and merged to form larger cracks. It is important to control the maximum strain of the weld seam during the forming to avoid possible harmful damage.

1 Introduction

With the development of the aerospace field, its requirements for lightweight and reliability are gradually increasing 1. Titanium alloy tailor-welded components have excellent comprehensive properties and are widely used in the aerospace field 2. The safety performance of weld seam in titanium alloy welded components is crucial in aerospace. In the process of high-temperature plastic deformation, titanium alloy weld seam is more likely to produce voids and cracks than base metal 3 4. At present, in terms of the research on the damage behaviour of titanium alloy weld seam, scholars mainly study the damage behaviour during the uniaxial tensile process. Lavogiez 5 studied the plastic damage initiation

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mechanism in titanium alloy and weld seam by in-situ tensile tests. In martensite microstructure, cracks are first initiated at pre-β grain boundaries and specific interfaces at 45° from the tensile direction. Ren 6 found that cracks mainly propagate in the zigzag path during the uniaxial tensile process in titanium alloy, and grain boundaries play an obstacle role in crack propagation. During the forming process of tailor-welded components, the weld seams are usually subject to complex stress state. However, there are few reports on the damage behaviour of weld seam under complex stress state.

In this work, the damage behaviour of titanium alloy weld seam during hot gas pressure forming was studied by experiment and simulation. Firstly, the damage evolution of a cup-shaped part in the hot gas pressure forming process was studied by simulation. Then, the hot gas pressure forming experiments of tailor-welded blank were carried out. The microstructure of the cup-shaped part at different positions was characterized by scanning electron microscopy. Finally, the damage behaviour of the welded blank in hot gas pressure forming was analyzed using simulation and experimental results.

2 Experiment and simulation

2.1 Experiment

The TA15 titanium alloy belongs to the near-α type titanium alloy and the nominal composition is Ti-6.5Al-2Zr-1Mo-1V. The initial thickness of TA15 titanium alloy used in this paper is 3.5 mm on average. The blank was welded by laser beam welding. The welding speed is 1.8 m/min, and the welding power is 3 kW.

In this paper, a cup-shaped part was formed, which has an inner diameter of 60 mm, a depth of 25 mm, and a fillet radius of 5 mm. The pressure loading path adopts constant pressure loading and the loading pressure was 8 MPa. The forming temperature was 900 ℃. First, the forming tools were heated to the target temperature, and then the titanium alloy laser-welded blank was placed into the forming tools and soaked for 5 minutes. After the soaking, the laser-welded blank and dies were sealed and then the compressed argon gas was loaded to form the cup-shaped part. After the forming was completed, the cup-shaped part was taken out immediately for water quenching. More details about the forming apparatuses could be found in our previous publication [7].

2.2 Simulation

A finite element simulation of hot gas pressure forming was carried out using the Abaqus software. The forming tool was set as a discrete rigid body, the element type was R3D4, and the mesh size was 3 mm. The blank is round blank with a diameter of 120 mm. The weld seam is located in the centre of the blank with a width of 3 mm. The welded blank used solid elements, the element type was C3D8R, and the mesh size was 1 mm. The GTN damage model established in previous work [8] was used for the constitutive model of the weld seam, and the stress-strain curve obtained by high-temperature uniaxial tensile was used for the constitutive model of the base metal.

3 Results and discussion

3.1 Finite element simulation of hot gas pressure forming

Fig. 1 shows the distribution of the equivalent strain of the welded blank at different holding time under condition of 900 ℃ and 8 MPa. When the pressure holding time was 60 s, as shown in Fig. 1(a), the strain at the flange fillet of the welded blank at the free bulging stage was much higher than that at the bottom. As shown in Fig. 1(b)~(e), the strain of the bottom region increased continuously during the forming of the bottom fillet. The deformation of the weld seam at the bottom was much lower than that of the base metal, and the deformation nonuniformity of the weld and base metal at the bottom increased gradually. At the side wall and bottom fillet of the cup-shaped part, the strain of the weld seam is smaller due to the weld's higher strength than the base metal and the base metal near the weld seam bears more deformation.

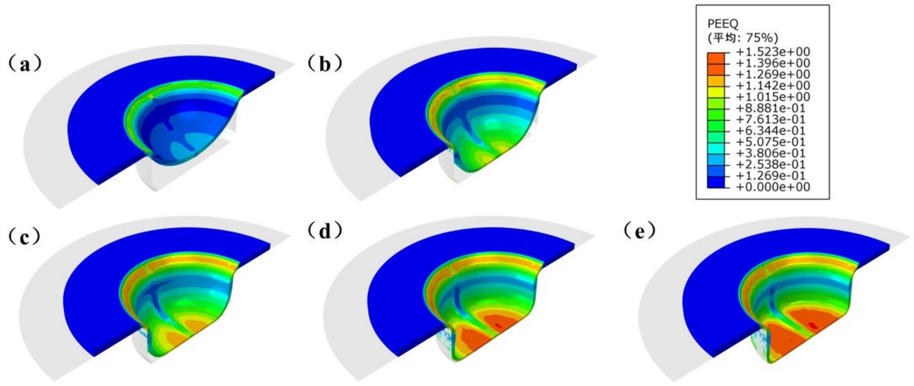

Fig. 1. Distribution of equivalent strain of the welded blank at different holding time under condition of 900℃ and 8MPa. (a) 60s (b) 120s (c) 150s (d) 200s (e) 300s

Fig. 2 shows the distribution of the void volume fraction of the weld seam at different holding time under condition of 900 ℃ and 8 MPa. When at the free bulging stage, the damage is mainly concentrated at the flange fillet, as shown in Fig. 2(a). With the increase of the holding time, the damage of the weld seam of the bottom increases gradually. When the holding time was 120 s, the void volume fraction of the weld seam at the flange fillet and at the bottom centre was about 7.34 % and 2.06 %, respectively. When the holding time was 300 s, the void volume fraction of the weld seam at the flange fillet and at the bottom centre was about 7.89 % and 2.49 %, respectively. This indicated that after the bottom of the cup-shaped part was in contact with the die, the damage of the weld seam at the flange fillet and the bottom grew slowly. The damage growth mainly occurred at the free bulging stage, and the damage at the flange fillet was always greater than that at other areas during the whole forming process.

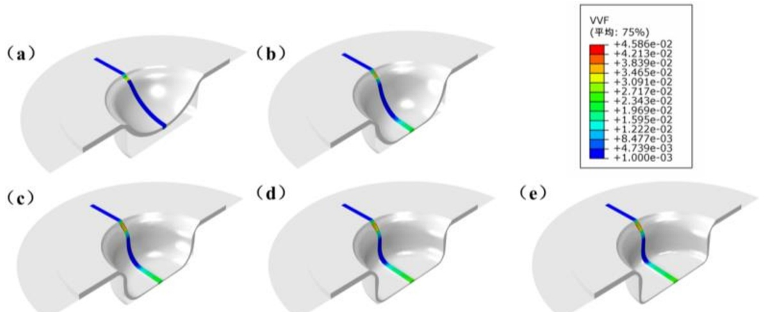

Fig. 2. Distribution of void volume fraction of the weld seam at different holding time under condition of 900℃ and 8MPa. (a) 60s (b) 120s (c) 150s (d) 200s (e) 300s

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Fig. 3 shows the evolution of void volume fraction at different positions. The damage of the inside fillet near the flange developed rapidly, because the inside fillet near the flange bore more deformation at the free bulging stage. The damage growth of the outside fillet near the flange is much smaller than that of the inside fillet near the flange. Due to the friction force, the deformation of the outside fillet near the flange is more difficult after contact with the die. The damage of the bottom centre developed slowly at the free bulging stage but rapidly at the bottom forming stage, and then it gradually became stable due to the effect of friction force. The strain of weld seam at the side wall and the bottom fillet was smaller; therefore, the damage of the side wall and the bottom fillet increased barely.

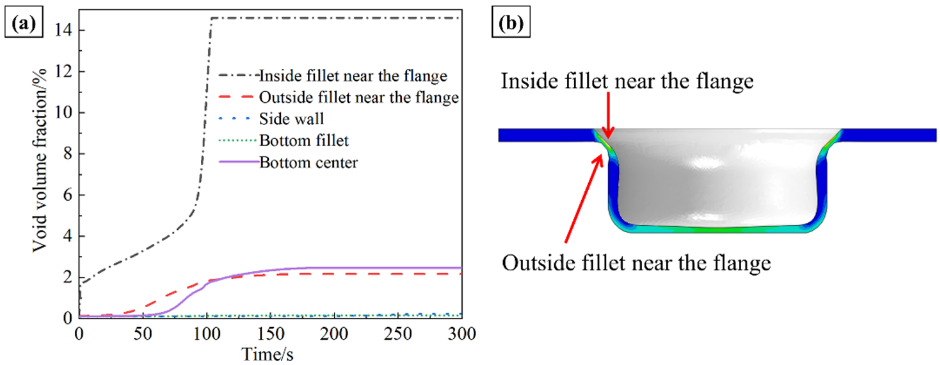

Fig. 3. (a) The evolution of void volume fraction at different positions (b) Schematic diagram of inside and outside fillet near the flange position.

3.2 Damage evolution during hot gas pressure forming

Hot gas pressure forming of the cup-shaped part with the welded blank was performed to explore the damage evolution of the weld seam at different forming stages, and the microstructure of the weld seam at the bottom center was characterized by scanning electron microscopy. Fig. 4 shows the cup-shaped parts and the damage of the bottom center at different forming stages under condition of 900 °C and 8 MPa. As shown in Fig. 4 (a_1) and (a_2), the welded blank has not been contacted with the die and is at the free bulging stage. The voids and cracks in the weld seam were relatively few. As shown in Fig. 4 (b_1) and (b_2), most of the bottom area of the cup-shaped part has been formed and contacted with the die. Due to the increasing strain, the number of cracks increased and the small cracks grew, expanded, and merged to form larger cracks gradually. In the forming stage of bottom fillet as shown in Fig. 4 (c_1), the bottom fillet and side wall contacted with the die gradually. The cracks further expanded and some larger internal cracks formed by the combination of multiple cracks can be observed in Fig. 4 (c_2). When the cup-shaped part has been fully formed (Fig.4 (d_1)), a surface crack with a size of about 400 μm was observed in Fig. 4 (d_2), which was generated by the cracks and voids near the surface by continuous growth and merger. The evolution of the damage during the experiment is consistent with the finite element simulation results.

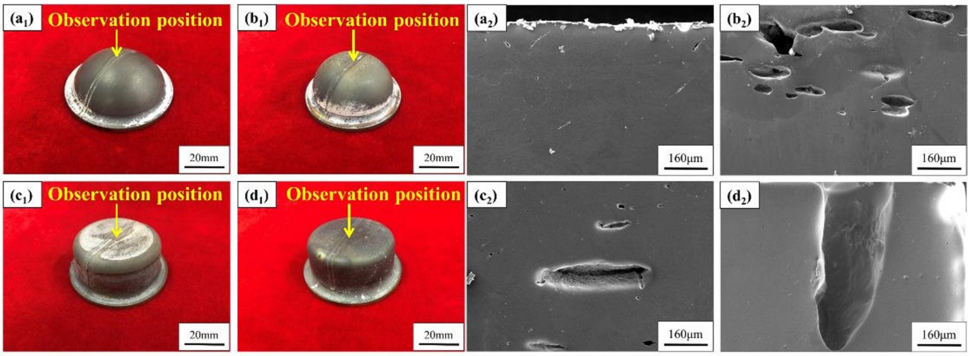

Fig. 4. The cup-shaped parts and the damage of the bottom center at different forming stages under condition of 900℃ and 8MPa. (a_1) (a_2) free bulging stage (b_1) (b_2) bottom and side wall forming stage (c_1) (c_2) fillet forming stage (d_1) (d_2) form completed

Fig. 5 shows the damage to the cup-shaped part at different positions. Fig. 5(a) is at the bottom centre. The damage is mainly concentrated on the outer surface. Fig. 5(b) is at the bottom near the fillet, where the number of voids and cracks increased significantly. The size difference between cracks is also significant. Some cracks have just been generated, and some have become large ones after growing and merging. Fig. 5(c) and (d) are at the bottom fillet and side wall, respectively. The damage at these two places is relatively low with a small number of voids and cracks. It should be noted that apparent damage was also observed in the inside fillet near the flange area, which could be found in our previous work [8]. It can be concluded that the damage during the hot gas pressure forming process of the cup-shaped part was mainly concentrated at the inside fillet near the flange and the bottom area. The damage is lower at the bottom fillet and side wall area. In this paper, the maximum equivalent strain of the weld seam is as high as 1.5, therefore lots of cracks were observed. In the actual forming, one should control the maximum strain of the weld seam to avoid possible cracks.

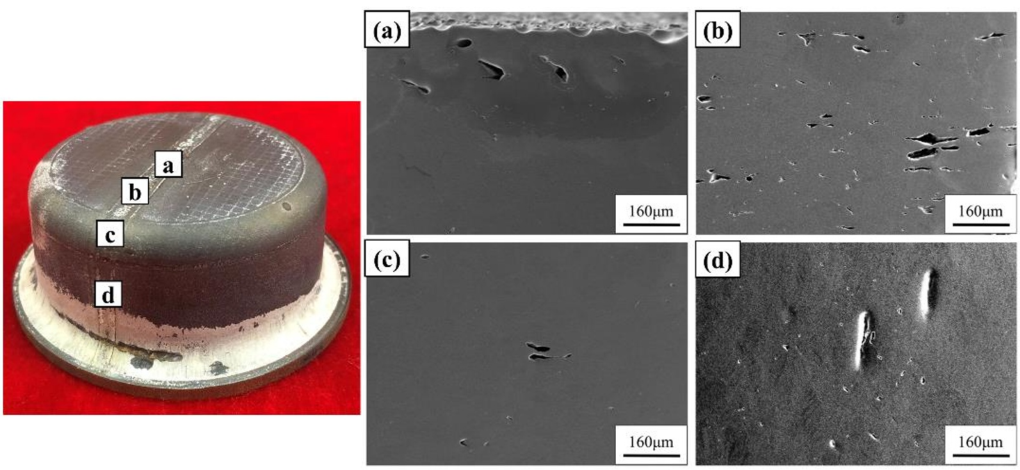

Fig. 5. Damage of cup-shaped part at different positions (900℃、16MPa、5min) (a) bottom centre (b) bottom near the fillet (c) bottom fillet (d) side wall.

4 Conclusions

In this paper, the damage behaviour of the weld seam during the hot gas forming process was studied. The main conclusions are as follows:

(1) The GTN damage model used in the simulation could predict the damage evolution of the weld seam during the hot gas pressure forming of the welded titanium alloy blank. The damage of the weld seam during hot gas pressure forming was mainly related to the strain. The void volume fraction of the weld seam increased gradually with the strain.

(2) The forming of the cup-shaped part includes two stages of free bulging and the forming of the bottom fillet. The strain at the flange fillet is the largest at the free bulging stage. As the forming time increases, the strain at the bottom gradually increases to the maximum. The strain of the weld seam is always less than that of the base metal around it due to its higher deformation resistance.

(3) During the hot gas pressure forming of the cup-shaped part, the damage of the inside fillet near the flange develops most rapidly, and it is easy to crack. The damage of the side wall and bottom fillet develops slowly. The damage of the bottom centre develops slowly at the free bulging stage. After the bottom of the cup-shaped part contacts the die, the damage develops rapidly and then reaches a stable level gradually.

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