Microstructure control in local loading forming of large-scale complex titanium alloy component

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Abstract

To control the microstructure and performance of large scale complex titanium alloy component by local loading forming, the effect of processing on microstructure in local loading forming was investigated by a through-process finite element model. It is found that the volume fraction of primary equiaxed $\alpha$ decreases with temperature, deformation speed and loading pass. The $\alpha$ grain size increases with temperature and loading pass but decreases with deformation speed. The homogeneity of the grain size can be improved by increasing deformation temperature and loading pass, or decreasing loading speed.

1. Introduction

The large scale complex titanium alloy component has been gaining increasing application in aircrafts as it can satisfy the demand of light weight and high performance (Yang et al., 2011). Forging is commonly used to manufacture such component for obtaining specific microstructure and performance along with shaping (Lütjering and Williams, 2007). However, the titanium alloy exhibits low ductility, high deformation resistance and strong microstructural sensitivity in high temperature deformation. Meanwhile, the large scale complex structure results in
increased forming load and defects. Thus, it is difficult to form the large scale complex titanium alloy component by traditional forging process. To this end, a local loading forming method was proposed (Yang et al., 2011), as shown in Fig.1. In local loading forming, the component is formed by accumulation of deformation imposed to part of the billet (Sun and Yang, 2009). Combined with isothermal forming or hot die forging, the workpiece can be formed at a relatively low speed without die chilling. By controlling the material flow, reducing loading area and enhancing the formability of material at each forming step, the local loading forming can reduce the required load and control the forming defects.

Microstructure control is critical to the application of local loading forming. The multi-step unequal deformation may result in diverse microstructures after local loading forming (Fan et al., 2010). By adopting proper processing parameters, it is possible to control the unequal deformation and to obtain the required microstructure. By now, a lot of analog experiments have been carried out to investigate the microstructural development in local loading forming (Fan et al., 2011). However, the relationship among processing, unequal deformation and microstructure needs further investigation.

In the present work, the deformation behavior and microstructure evolution in local loading forming of large scale titanium alloy component were investigated using finite element simulation. The effect of processing on microstructure was revealed. The results can be used to optimize the local loading forming process.

2. Research method (Fan et al., 2014)

2.1. Material

The material employed is a near α TA15 titanium alloy with the chemical composition (mass %) of 6.06 Al, 2.08 Mo, 1.32 V, 1.86 Zr, 0.30 Fe and balanced Ti, and measured β transus temperature of 990 °C. A typical forming process of the material involves primary processing in which ingots are converted into general mill products, and secondary processing for shaping mill products into actual components. The primary processing breaks down the as-cast structure, and transforms the lamellar structure to equiaxed structure. The secondary working is carried out below the β transus temperature to retain the equiaxed α phases and obtain bimodal or equiaxed structure. The local loading forming is a secondary working process. The grain size and volume fraction of the equiaxed α phases can be affected by the processing, which influences the service performance of the final product.

2.2. Local loading forming procedure

The large scale complex component involved in the current study is an integral bulkhead (Fig. 1(a)). It is formed from a simple unequal-thick billet.

In local loading forming, the bottom die is kept integral, while the originally integral top die is separated into Top Die 1 and Top Die 2 (Fig. 1(b)). The local loading forming is implemented by several loading passes. Each
pass includes two steps. In the first step, the left part of the workpiece is deformed by Top Die 1. In the second step, the other part is deformed by Top Die 2 while Top Die 1 acts as a constraint. These two steps are repeated until the whole component is formed.

The forming process is carried out on a single-action hydraulic press. To adjust the top dies, it is necessary to cool the dies and billet. In each loading step, the workpiece is heated to the deformation temperature, held for 1.5h for homogenization, deformed and cooled to room temperature.

2.3. Finite element modeling of the local loading forming

The finite element simulation has become an important tool to investigate the plastic forming process. To predict the microstructure evolution in local loading forming, a through-process FE model has been established by the authors (Fan et al., 2014). In this model, the main microstructure changes are considered, including the phase transformation in heating and cooling, the coarsening in holding and the dynamic microstructural developments in deformation. The model is employed to bridge processing, deformation and microstructure (Fig. 2).

Fig. 2. Comparison of the predicted volume fraction (a) and grain size (b) of primary α phases with experiment (Fan et al., 2014).

3. Results and discussion

3.1. Microstructure under different heating temperatures

The heating temperature is commonly 20-100 °C below the β transus temperature. Fig. 3 shows the volume fraction of the primary equiaxed α under different heating temperatures. The variation of α fraction on the workpiece is similar under different temperatures. The α fraction is lower in the first loading region than in the second loading region. In the first loading region, the α fraction is higher in the webs than in the ribs. In the second loading region, the α fraction varies at different parts of the workpiece due to the variation of deformation and thermal history.

The α fraction decreases with temperature as the initial α fraction of the billet decreases with temperature. Meanwhile, the distribution of α fraction becomes more inhomogeneous at high temperatures. This is more significant in the second loading region. This is because the temperature drop increases with temperature. The supersaturation of the solute is increased while the diffusion is accelerated. The diffusional growth of the equiaxed α is promoted. The effect of deformation and thermal history on the diffusional growth is enlarged. Thus, the inhomogeneity of α fraction is increased.

Fig. 4 presents the variation of grain size of the primary α phases under different heating temperatures. It is found that the grain size decreases with temperature. This is because the diffusion of the solution is suppressed under lower temperatures. The static coarsening during holding is decreased while the dynamic break-down of the α during deformation is increased. Thus, the microstructure is finer under lower temperatures.
However, the grain size distribution is more homogeneous at high temperatures. The break-down of primary α phases is weakened with increasing temperature. The grain size distribution is less affected by the unequal deformation in local loading forming, which increases the homogeneity of the grain size distribution.

![Fig. 3. Volume fraction of primary equiaxed α under different deformation temperatures: (a) 920; (b) 950; (c) 970 °C.](image)

![Fig. 4. Grain size of primary equiaxed α under different deformation temperatures: (a) 920; (b) 950; (c) 970 °C.](image)

**3.2. Microstructure under different deformation speeds**

The local loading forming is carried out on a hydraulic press. To avoid impact, the loading speed is relatively low. In the current work, a maximum die speed of 5mm/s is adopted, such that the maximum average strain rate is about 0.1s\(^{-1}\).

![Fig.5. Volume fraction of primary equiaxed α under different loading speeds: (a) 0.2; (b) 1; (c) 5 mm/s.](image)
Figure 5 illustrates the variation of primary equiaxed $\alpha$ under different deformation speeds. The variation of $\alpha$ fraction on the workpiece is similar under different loading speeds. The $\alpha$ fraction decreases with deformation speed and its distribution becomes more homogeneous. This phenomenon is significant in the second loading region. The deformation time is shortened with increasing speed. The time dependent diffusional growth process is suppressed. Thus, the $\alpha$ fraction decreases. On the other hand, the effect of deformation and thermal history on the diffusional growth is weakened with decreasing deformation time. Thus, the microstructure becomes more homogeneous. The temperature drop of the first loading region is fast in the second loading step while the deformation degree is small. The $\alpha$ fraction is less affected by the diffusional growth. Therefore, the $\alpha$ fraction of the first loading region is insensitive to deformation speed. For the second loading region, diffusional growth is more significant if the deformation time is long. The $\alpha$ fraction would increase sharply under low speed.

Figure 6 shows the grain size of the primary equiaxed $\alpha$ under different loading speeds. It is found that the microstructure is refined slightly under higher loading speed. This is because the high deformation speed suppresses the dynamic restoration and increases the crystal defects. Thus, the break down of $\alpha$ grains is promoted. Meanwhile, there is less time for the coarsening and diffusional growth of $\alpha$. Thus, the grain size decreases.

It is also found that grain size distribution is more uniform under low deformation speed. The grain size is mainly affected by the unequal deformation associated with the complex shape of the component. Grain refinement is more significant under large strain rate. Thus, the effect of unequal deformation on the grain size distribution is enhanced under higher deformation speed.

3.3. Microstructure under different loading passes

To coordinate the unequal deformation, two-pass local loading forming can be employed, such that the unequal deformation in each step is decreased.
Figure 7 compares the volume fraction of primary equiaxed $\alpha$ under different loading passes. It can be found that the $\alpha$ fraction of the component is decreased in two-pass local loading. Its distribution becomes more uniform. The difference between the first loading region and second loading region is decreased. It can be deduced that the deformation degree and thermal history in the last loading step determines the $\alpha$ fraction. The deformation degree and loading time are decreased when two-pass loading is adopted. Thus, the $\alpha$ fraction is decreased. As the unequal deformation decreases, the distribution of $\alpha$ fraction becomes uniform.

It can be found from Fig.8 that the grain size of primary equiaxed $\alpha$ is larger in the two-pass loading than in the one-pass loading. In two-pass loading, the workpiece undergoes repeated heating and holding processes. Grain coarsening is more notable. Meanwhile, the total deformation degree varies little, i.e., the grain refinement due to plastic deformation is similar to that in one-pass loading. Thus, the grain size is increased. However, the grain size distribution in two-pass loading is similar to that in one-pass loading.

3. Conclusions

The effect of processing on microstructure in local loading forming of large scale complex titanium alloy component was investigated. It is found that the volume fraction of primary equiaxed $\alpha$ decreases with temperature, deformation speed and loading pass. The distribution of $\alpha$ fraction becomes more uniform with decreasing temperature and increasing deformation speed and loading pass. The $\alpha$ grain size increases with temperature and loading pass but decreases with deformation speed. The homogeneity of the grain size can be improved by increasing deformation temperature and loading pass, or decreasing loading speed. Further work on experiment will be done to validate the results.

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References