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Through-process macro–micro finite element modeling of local loading forming of large-scale complex titanium alloy component for microstructure prediction

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ABSTRACT

The intrinsic multi-heat unequal deformation behavior of the local loading forming requires a through-process macro–micro model to characterize the microstructure evolution during the forming process. In the present work, the phenomena and mechanisms of microstructural developments in local loading forming of titanium alloys are summarized. Mechanism-based unified material models, which characterize the through process microstructure evolution, are developed for integrated prediction of constitutive behavior and microstructure. A through-process macro–micro finite element model is established for the local loading forming of large scale complex titanium alloy component. The model can predict the microstructure evolution as well as macroscopic deformation in multi-step local loading forming process. Model predictions are in good agreement with experimental results. The microstructure evolution in local loading forming is investigated by the established finite element model. It is found that the thermo-mechanical processing route greatly affects the volume fraction of primary alpha but has little influence on the grain size in local loading forming

1. Introduction

To satisfy the demand for high performance and light weight in aerospace industries, large-scale complex titanium alloy components have gained increasing applications. These components often serve as the key load-bearing structure under severe working conditions. Thus, the microstructure and mechanical properties must be strictly controlled besides the shape. Hot forging is a competitive route for manufacturing such components, as it can tailor the microstructure and performance along with shaping. However, it is difficult to form the large-scale complex titanium alloy component by the traditional hot forging technique, as the difficult-to-deform material and the complex shape employed can result in enormous forming load, increased forming defects, and degraded service performance. Alternatively, a local loading forming method has been proposed by Yang et al. (2011) to form the large-scale complex titanium alloy component. During local loading forming, load is applied to part of the billet and the component is formed by accumulation of local deformation, as shown in Fig. 1 (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.

Severe unequal deformation takes place in local loading forming of the large-scale complex titanium alloy components. The multistep unequal deformation can affect the properties of the finial product, as the microstructure of titanium alloy is sensitive to processing. Fan et al. (2010) carried out experimental investigation on the phenomena and mechanisms of microstructure developments in local loading forming of large scale titanium alloy component. They found that the volume fraction and morphology of the constituent phases are greatly affected by the deformation path. However, to optimize the local loading forming, further work should be done on quantitatively relating the microstructure with processing.

By decades, the finite element (FE) simulation has become an important tool for the design and optimization of the hot forging process. The FE simulation has been used to investigate the macroscopic deformation in local loading forming of large-scale complex titanium alloy component by Zhang et al. (2010). To predict the microstructure evolution, it is still necessary to implement appropriate microstructure model into the FE model. This method has been used to the hot working of titanium alloy parts. For instance, Hu et al. (1999) employed a coupled thermo-mechanical

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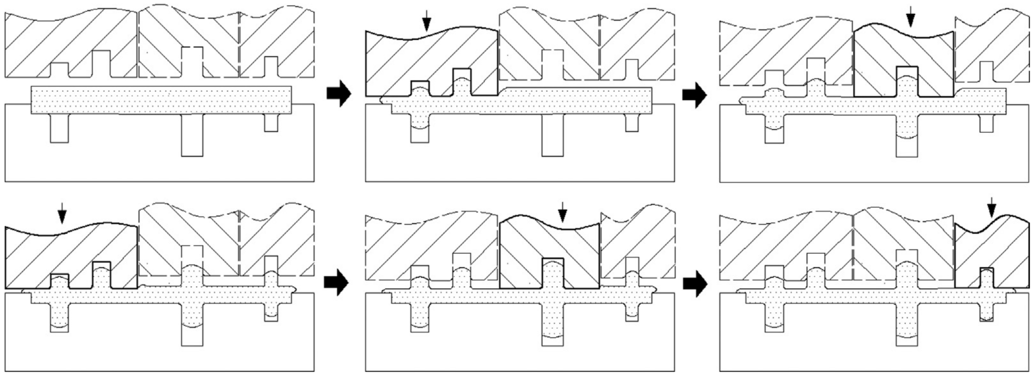

Fig. 1. Schematic diagram of the local loading forming (Sun and Yang, 2009).

FE model to predict the microstructure parameters in hot die forging of titanium alloy aerofoil blade. However, most of the models only involved the microstructure developments in the deformation stage. Being different from the traditional hot forging process, the local loading forming is a multi-step hot forming process consisting of a series of thermal cycles. A thermal cycle includes several operations, such as heating, holding, deformation and cooling. Each operation may influence the microstructure and performance of the hot forged workpiece. Thus, a through-process numerical model, which considers the microstructure evolution in all operations and steps, is necessary for the local loading forming process. Gottstein (2007) pointed out that the through-process modeling has been applied to a lot of forming processes, such as the rolling of aluminum sheet and the ring rolling of steel. However, the modeling approach should be determined by the material as well as the thermo-mechanical processing route involved. The microstructure evolution varies from material to material. Besides, the thermo-mechanical processing route in local loading forming is quite different from that in other forming processes. Thus, the through-process modeling of the local loading forming of the large-scale complex titanium alloy component needs further investigation.

The key challenge in through-process modeling is to develop a reliable microstructure model which characterizes the microstructure developments in the whole process. Grong and Shercliff (2002) summarized that there are generally four approaches for microstructure modeling of metals: the empirical methods, advanced statistical methods, physically based internal state variable (ISV) methods and the direct simulation approaches. The empirical methods link the microstructure and processing parameters explicitly with empirical equations. However, they have limited predictive power for complex processes. The advanced statistical methods (such as the artificial neural networks), can handle the strong non-linearity between inputs and outputs and exhibits good accuracy. However, they offer no physical insights, and are not suitable for processes with complex history. The direct simulation approaches (such as Cellular Automaton simulation and Monte Carlo method) offer mesoscopic simulation of aggregates of grains one-to-one. However, they are too time-consuming to be coupled with macroscopic FE model. The physically based internal state variable methods describe the underlying phenomena in terms of a small number of internal state variables. They depict the microstructure developments by a simultaneous set of differential equations. Thus, they are suitable for processes with complex thermo-mechanical history. By relating flow stress to the ISVs, they can characterize the effect of microstructure evolution on constitutive behavior. The physically based internal state variable methods have been applied to titanium alloys. Bai et al. (2013) developed a set of mechanism-based elastic-viscoplastic constitutive equations of the Ti–6Al–4V alloy, in which the globularization of secondary alpha, dislocation density, deformation induced temperature rise and phase transformation were modeled. However, the static microstructure developments are not considered in their work. Luo et al. (2010) proposed a unified constitutive model with aim to predict the flow stress and the grain size of alpha phases in high temperature deformation of Ti–6Al–4V alloy. However, the model only considered the microstructure evolution in the deformation stage. For through-process modeling, it is necessary to integrate the microstructure mechanisms which prevail in other stages (such as heating and cooling).

In the present work, the mechanisms of microstructure evolution in the local loading forming of titanium alloy were identified. Based on identified mechanisms, material models considering the microstructure evolution in the whole process were established and a through-process modeling scheme was proposed. The material models were implemented into the FE model to develop a through-process numerical model of local loading forming. The established numerical model was used to investigate the origins of non-uniform microstructure in local loading forming of large scale complex titanium alloy component.

2. Local loading forming process

The component involved in the present work is a large-scale integral bulkhead, as shown in Fig. 2. It has densely crossed ribs with height-to-width ratio of the order of 3. The thickness of the webs is close to the width of the ribs. The component is more than 1 m in length and width. However, the widths of the ribs scale 10 mm order of magnitude. The material employed is a near alpha TA15 titanium alloy (Ti-6Al-2Zr-1Mo-1V).

The local loading forming is carried out on a single-action hydraulic press with a forming unit shown in Fig. 3 (Sun et al., 2012). The bottom die (8 in Fig. 3) is kept integral, while the originally integral top die is separated into two parts: Top Die 1 (5) and Top Die 2 (6). A spacer (4) is implanted between the Top Die 1 (5) and the Insulation Plate (3) to adjust the relative position of the two top dies. The protruding die deforms the workpiece while the other die works as a constraint. The loading region can be changed by adjusting the relative position of the two top dies. All the dies are heated by a furnace surrounded to avoid die chilling. To minimize macroscopic defects, close die forging is adopted, as suggested in Sun et al. (2012). An unequal-thick billet is used to eliminate under-filling.

The local loading forming is implemented by several loading steps. In each step, a specific spacer is placed between Top Die 1 and the Insulation Plate to set the relative position of the top dies. The workpiece is locally deformed by the protruded die. By accumulation of deformation in different regions, the whole component can be formed. To adjust the top dies, it is necessary to cool the whole