Some advances in plastic forming technologies of titanium alloys

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Abstract

To satisfy the ever increasing demands of high performance and light weight in high-end equipments, the titanium components are designed to have complex shape and specific performance. Research and development of advanced plastic forming technologies are of great importance to manufacturing these titanium products with low cost and short cycle. The local loading forming technology with advantages in reducing forming load, enlarging forming size and enhancing forming limit and precision through control of unequal deformation provides a feasible way to manufacture the high performance and light weight titanium components (large-scale, integral, complex, thin-walled) widely used in aircrafts and shows a good developing prospect. This paper presents the state of the art of local loading forming technology and its applications in manufacturing titanium components in the authors’ laboratory, including the isothermal local loading forming of large-scale complex TA15 bulkhead, and heat rotary draw bending of large-diameter thin-walled titanium tube.

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1. Introduction

The titanium alloy is an advanced light weight metallic material with high strength, low density and excellent corrosion resistance. It has been gaining extensive applications in aviation, marine and medicine. 70% of the
titanium is used for aerospace applications (Boyer and Williams, 2011). To satisfy the ever increasing demands of high performance and light weight in aircrafts, the titanium components are designed to have complex shape and specific performance. Plastic working is the most applicable forming method as it can tailor the microstructure while shaping. However, the titanium alloy exhibits relatively low ductility, low elastic modules, high yield stress and strong anisotropy, which reduce the forming limit and precision in plastic forming. Meanwhile, the microstructure of titanium alloys is sensitive to processing. It is difficult to control the microstructure evolution to obtain the desired service performance.

Much works have been carried out for fabrication of titanium components with high precision, high performance and low cost. Part of these studies focus on the plastic deformation behaviour and constitutive modelling of titanium alloys. Khan et al. (Khan and Yu, 2012; Khan et al., 2012), Nixon et al. (2010), and Ghosh and Anahid (2013) quantified the plastic anisotropy behaviour of titanium alloy under different loading conditions and established different anisotropic constitutive models. Khan et al. (Khan et al., 2007; Khan et al., 2004) successfully modelled the response of titanium alloy under various strain rates from quasi-static to dynamic loading regimes using a modified Khan-Huang-Liang (KHL) equation. Fan and Yang (2011) developed an internal-state-variable based self-consistent constitutive model considering solution strengthening, Hall-Petch effect, dislocation interaction and dynamic recrystallization, which is capable of predicting the flow stress and microstructure evolution simultaneously during hot working of two-phase titanium alloys. Another popular research field is the microstructure and texture evolution during deformation. Zhang et al. (2012) investigated the microstructure and texture development during cold deep drawing of CP-Ti and found that the deformation twinning weakens the initial texture by randomizing the orientations of crystals, especially for the recrystallization texture. Lin et al. (2013) carried out series of tensile tests to study the microstructure and texture evolution of a near-α titanium alloy at high temperature. They found that the initial textures were weakened or eliminated by the dynamic recrystallization process. Gao et al. (2012) obtained four types of microstructure (widiastätten, bi-modal, tri-modal and basket-weave microstructure) under different temperature routes and analyzed their development processes in the isothermal local loading forming of TA15 alloy. These basic researches lay the theoretical fundament for the prediction and control of shape and microstructure during plastic forming of titanium component.

For the plastic forming technology of titanium alloy, higher precision, more force-saving, and higher efficiency have become the new development trends (Yang et al., 2008). Although traditional plastic forming technologies, e.g. free forging, isothermal forging and extrusion, etc., still play an important role in the plastic forming of titanium alloy, some innovative plastic forming technologies were proposed recently to satisfy the ever increasing requirements in performance and shape of new titanium components. For example, the severe plastic deformation (SPD) technology, including equal channel angular pressing, hydrostatic extrusion, accumulative roll bonding, etc., have been developed to produce Ultrafine-grained titanium alloys which possesses better comprehensive properties (Yang et al., 2011a). Besides, the local loading forming technologies including continuous local loading forming and intermittent local loading forming, e.g. isothermal local loading forming, tube bending, hot ring rolling and spinning, have attracted much more attention in recent years. This technology with advantages in reducing forming load, enlarging forming size and enhancing forming limit and precision through control of unequal deformation provides a feasible way to manufacture the high performance and light weight titanium components (large-scale, integral, complex, thin-walled) widely used in aircrafts and shows a good developing prospect (Yang et al., 2011b).

However, the local loading forming is a complicated process with coupling effects of multi-die, multi-parameter and multi-field, which brings challenges for the integrated control of shape forming and microstructure evolution, and the through-process optimization and robust control of forming process. To solve the challenges, Lab of Precision Plastic Forming from Northwestern Polytechnical University have done systematic and in-depth investigations on the multi-scale through-process modelling, regulation and control mechanisms of microstructure and macro-defects under unequal deformation and through-process optimization in local loading forming of titanium alloy component, and made some progress. The present paper reports these developments which not only enriches the advanced theory in plastic forming of titanium alloy, but also promote the manufacturing technology of high-end equipments.
2. Multi-scale through-process modeling of local loading forming of titanium alloy

Currently, the multi-scale through-process modeling has become an important method for design and optimization of the plastic forming process. With this method, we can conduct systematic investigation on the mechanisms of macroscopic deformation and microstructure evolution, regulation of unequal deformation, and optimization of the forming process (McDowell, 2010). Thus, a multi-scale through-process modeling scheme, consisted of a microscale cellular automaton model, a mesoscale crystal plasticity model, a coupled macro-microscale internal-state-variable model, and a macroscale FE model, was proposed for local loading forming of complex titanium components.

2.1. Internal-state-variable constitutive model coupled microstructure evolution

In the hot working of titanium alloy, the macroscopic deformation strongly interacts with the microstructure evolution. A constitutive model coupled microstructure evolution is essential for bridging the macroscopic deformation and microstructure evolution. However, the coexistence of hcp α phase and bcc β phase in two-phase titanium alloy causes significant heterogeneous deformation and complicates the microstructure evolution as well as the constitutive response, which increase the modeling difficulty greatly. To solve this problem, the mobile grain boundary area, immobile grain boundary area and dislocation density were first introduced as state variables to describe the interaction of deformation and dynamic recrystallization (DRX) of constituent phases (Eqs. (1) and (2)); The effect of α phase on the evolution of β phase was modeled by considering particle stimulated nucleation and exerting drag force on boundary migration (Eqs. (3) and (4)); A viscoplastic self-consistent scheme was applied to characterize the heterogeneous deformation of two constituent phases. Synthetically, an internal-state-variable based self-consistent constitutive model was founded for the hot working of titanium alloys, which enables the unified prediction of flow stress and microstructure evolution (Fan and Yang, 2011). This model presents good commonality for many two-phase titanium alloys, such as Ti-6Al-4V, IMI834 and TA15, partial applications are shown in Fig. 1.

\[
\frac{dS_m}{dt} = \frac{nS_m V^4 \pi \sigma^2}{2} - \frac{2S_m}{\rho} v - \beta S_m \left( \frac{S_m}{S_0} \right)^{\frac{3}{2}} v
\]

\[
\frac{dS_m}{dt} = -nS_m V^4 \pi \sigma^2 - \beta S_m \left( \frac{S_m}{S_0} \right)^{\frac{3}{2}} v
\]

\[
\frac{dS}{dt}_{\text{inactive}} = C \dot{\gamma}^\alpha \exp \left( \frac{Q_{\text{act}}}{RT} \right) \left( \frac{S_m + \kappa F}{R} \right)
\]

\[
p = \rho Gb^2 / 2 - c \rho \dot{\gamma}^\nu \frac{E V^3}{L}
\]

Fig. 1. Applications of the constitutive model: (a) predicted flow stress of Ti-6Al-4V, (b) predicted flow stress of IMI834, (c) predicted recrystallization kinetics of IMI834 (Fan and Yang, 2011).

2.2 Through-process coupled thermo-mechanical FE model for isothermal local loading forming

The local loading forming is a multi-step forming process and each step contains several operations: heating, holding, deformation and cooling. Each operation may influence the forming quality of the workpiece. Thus,
establishing a through-process FE model is necessary for deformation and microstructure control in local loading forming. Table 1 shows the microstructure evolution in each operation. A unified material model, which considers the microstructure developments in the whole process, was developed based on the identified mechanisms. Then, the material model was implemented into FE code to establish a through-process model for the local loading forming (Fan et al., 2014). The through-process model can predict macroscopic deformation and microstructure parameters in each loading regions and the transitional region (Fig. 2), which is in accordance with the experimental observations.

Table 1. Microstructure development in a single loading step (Fan et al., 2014).

<table>
<thead>
<tr>
<th>Operation</th>
<th>Microstructure evolution</th>
<th>Important parameters</th>
<th>Microstructure features</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heating</td>
<td>a→β transformation</td>
<td>Temperature</td>
<td>Phase fraction</td>
</tr>
<tr>
<td>Holding</td>
<td>Grain coarsening</td>
<td>Holding time</td>
<td>Grain size</td>
</tr>
<tr>
<td>Deformation</td>
<td>β→α transformation</td>
<td>Deformation parameters</td>
<td>Phase fraction</td>
</tr>
<tr>
<td>Cooling</td>
<td>β→α transformation</td>
<td>Cooling rate</td>
<td>Phase fraction</td>
</tr>
</tbody>
</table>

Fig. 2. Predicted distribution of temperature (a), strain (b), volume fraction (c) and grain size (d) after the local loading forming (Fan et al., 2014).

2.3. Crystal plasticity FE model coupled DRX evolution

The crystal plasticity finite element (CPFE) model works as a multi-mechanism and multi-physics platform, presenting the advantages of solving crystal mechanical problems under complex internal and external boundary conditions (Roters et al., 2010). It is an important tool to investigate the mechanism of multi-scale unequal deformation in local loading forming. Furthermore, the CPFE model can capture the local deformation information at the grain level which plays a key role in the microstructure change, providing vital information for microstructure modelling. DRX is an important metallurgical phenomenon and significantly influences the microstructure evolution and deformation behaviour in hot working of titanium alloy. So, establishing a CPFE model coupled DRX evolution is critical to study the synchronously responding DRX, thermomechanical behaviour and mesoscale unequal deformation in hot working of titanium alloy. However, the quantities of random nucleation and growth in DRX are difficult to characterize in mesoscale modelling, and the interaction of deformation and microstructure evolution makes the computation of CPFE model inefficient and instability. To this end, an equivalent approach to describe the nucleation and growth of DRX was proposed (Fig. 3), which reduces the complexity of DRX model and improves the efficiency and stability of CPFE model greatly. Besides, the shear strain rate of slip system calculated via crystal plasticity was employed to determine the dislocation density and nucleation rate of DRX (Eqs. (5) and (6)), which characterize the effect of deformation on microstructure evolution. Meanwhile, to express the effect of microstructure evolution on plastic response, the slip resistance is related to the dislocation density and microstructure (Eq. (7)). Then, an effective crystal plasticity constitutive model considering DRX was developed. The constitutive model was implemented into a mesoscale FE model based on the real microstructure of titanium alloy, such that a CPFE model coupled DRX based on real microstructure was established. The developed model can accurately predict the flow stress behavior, recrystallized grain size and texture evolution in hot working of titanium alloy, as shown in Fig.4. Moreover, this model can successfully applied to large deformation in bulk forming presenting good stability (Li et al., 2013; Wu et al., 2013a).
Fig. 3. Equivalent approach to describe the nucleation and growth of DRX: (a) actual microstructure; (b) spherical grains and recrystallized nuclei at grain boundary; (c) constant volume of the M-grain and R-grain; (d) R-grain’s growth and the repeated nucleation (Li et al., 2013).

\[
\dot{\rho}^{\text{DRX}} = c_1 \sqrt{\rho_{\text{DRX}}} \dot{\gamma}^{\text{DRX}}
\]

\[
\dot{n} = c_2 \dot{\gamma}^{\text{DRX}} \exp \left( -\frac{Q_{\text{recr}}}{RT} \right) \frac{r_0}{r}
\]

\[
s^{\text{DRX}} = \frac{1}{N} \left( c_3 \exp \left( -\frac{\theta}{\theta_0} \right) + k_4 \sqrt{\dot{\gamma}} \right) + c_4 \mu b \sqrt{\rho_{\text{DRX}}}
\]

2.4. Microstructure morphology evolution model

There exist many microstructural mechanisms in isothermal local loading forming of titanium alloy, such as grain coarsening, discontinuous dynamic recrystallization of β phase (β-DDRX) and continuous dynamic recrystallization of α phase (α-CDRX). These microstructural mechanisms can greatly affect the grain size and microstructure morphology of the material, thus influence the mechanical properties. To characterize the evolution of microstructure morphology, a cellular automaton (CA) model considering the above microstructural mechanisms was developed. As for the grain coarsening, the coarsening mechanisms controlled by diffusion along grain boundaries and through the bulk, the effect of solute drag and the anisotropic mobility of grain boundaries were modeled. While, in the modeling of β-DDRX and α-CDRX, the substructure growth, migration and dislocation density evolution were considered. Then, the CA model was coupled with the CPFE model. The CPFE model was conducted to acquire deformation parameters at the grain level, such as strain and crystal orientation, which were imported to the CA model in each simulation step to compute the effect of deformation on microstructure evolution. Finally, the microstructure morphology evolution model for hot working of titanium alloy was built. Fig. 5 gives the comparison between the experimental and predicted microstructure morphology (Wu, 2013; Wu et al, 2013b).

Fig. 4. Comparison of predicted results by mesoscale CPFE model with experimental measurements: (a) flow stress behavior; (b) recrystallized grain size; (c) texture (Li and Yang, 2012; Li et al., 2013).

Fig. 5 Comparison between the experimental (a, b) and predicted (c, d) microstructures of TA15 alloy under 1050°C, 0.01 s⁻¹ and different reductions: (a, c) 40%; (b, d) 60% (Wu, 2013).
3. Control of microstructure evolution and shape forming in local loading forming of titanium alloy

In the local loading forming of titanium alloy, the unequal deformation and microstructure evolution are very complex and have interaction, which usually leads to some microscale and macroscopic forming defects, e.g. coarsen microstructure, underfilling, folding, and so on. Revealing the role of unequal deformation on microstructure evolution and macro-defects will provide guidance for unified control of microstructure evolution and shape forming in the local loading forming of titanium alloy.

3.1. Microstructure evolution mechanisms and rules in whole process during local loading forming

The microstructural mechanisms in each operation, including heating, holding, deformation and cooling, during local loading forming were investigated by systematic experiments. The experimental results show that the coarsening mechanism of TA15 alloy during heating and holding phases varies with temperature as follows. The coarsening process was controlled by diffusion along grain boundaries at lower temperature, while mainly controlled by diffusion through the matrix at higher temperatures (Wu et al., 2013c). The deformation behaviour and mechanism were investigated by isothermal interrupted and uninterrupted compression tests (Fan et al., 2011b). The results show that the flow stress of TA15 alloy deformed in two-phase region exhibit low peak strain followed by obvious flow softening, and the flow softening is mainly related to the β-DDRX and α-CDRX. Extensive works were also conducted on the microstructure mechanisms during cooling after deformation by end quenching experiments and thermal simulation tests (Sun et al., 2013). It is found that for TA15 alloy the nucleation and growth of α-lamellae involved four steps, including nucleation of grain boundary α (α_{GB}), growth of α_{GB}, nucleation of Widmanstätten α (α_{WGB}), and growth of α_{WGB}, as shown in Fig.6. It was found for the first time that the mode of nucleation of α_{WGB} was interface instability rather than the traditional sympathetic nucleation, i.e. α_{WGB} nucleated through surface instability and the protuberance of α_{GB} and equiaxed α, and the α_{WGB} nucleus did not have an independent and complete surface. The growth of α_{WGB} started from a small protuberance and spread into a β grain with a sectorial morphology, to become lamellar instead of spiculate or oblate cuboid in shape, and the α_{WGB} usually grow faster than the thickening α_{GB} and equiaxed α.

Fig.6 Schematic nucleation and growth diagram for the α-lamellae when the titanium alloy was cooled from two-phase field: (a) new interface instability nucleation for α_{WGB}; (b) traditional sympathetic nucleation for α_{WGB} (Sun et al., 2013).

3.2. Microstructure control in local loading forming of titanium alloy

Among various morphologies of titanium alloy, the tri-modal microstructure possesses excellent comprehensive mechanical properties, which is pursued in the hot working of titanium alloys (Zhou et al., 2005). However, during local loading forming, the material in different regions undergoes complex unequal deformation and temperature route and varies with each other, leading to much difficulty in tailoring uniform tri-modal microstructure. To this end, a feasible analogue experiment was designed to simulate the multi-step unequal deformation behavior in local loading forming, as shown in Fig. 7 (Fan et al., 2011a). Based on the quantitative analysis of the microstructure results, it can be concluded that the tri-modal structure can be achieved by near-β forging followed by conventional forging in the last loading pass (Fig.8), and the volume fraction of each constituent phase in tri-modal structure is determined by the heating temperatures of the last two loading steps (Gao et al., 2012; Fan et al., 2012).
Fig. 7. Analogue experiment for local loading forming (one pass, two steps): (a) the first loading step; (b) the second loading step; (c) the processing route (Fan et al., 2011a).

Fig. 8. Microstructure of the sample deformed at 970°C in the first loading step and 950°C in the second loading step (a) the first-loading region; (b) the transitional region; (c) the second-loading region. (Gao et al., 2012)

3.3 Macro-defects mechanisms and control in local loading forming of large-scale complex component

In local loading forming, the transitional region connects the loading region with unloading region and undergoes very complex unequal deformation and material flow, which may cause some macro-defects such as folding, underfilling and flow lines disturbance. As a result, the transitional region needs more concerns. Among these potential forming defects, folding defect is the most sensitive to unequal deformation and restricts the forming limit (maximum reduction amount) in local loading forming. To solve such a challenge, a local eigen model of transitional region in the local loading forming of large-scale rib-web component was established first, through which the mechanism of forming defects of transitional region and their dependence on the processing parameters were studied by the combination of physical experiment and FE simulation (Fig. 9). Then, an adaptive folding index was successfully proposed to measure the severity of folding based on the local increase of the strain rate when a folding tends to appear (Eq. (8)). Based on the folding index, the critical value for judging folding defect was determined by quantities of random samples. At last, the maximum reduction amount under various geometry parameters in local loading forming of large-scale complex titanium components were successfully obtained by a stepwise searching method combining the folding index and judging criterion.

Fig. 9. Scheme of the local eigen model of transitional region (a), and simulation of folding defect formation (b).

\[
\phi_{\text{fold}} = \int_0^t \left( \frac{1}{\int_{\Omega_{\text{fold}}} ds \ s_{\text{ave}} \ \xi ds} \right) dt
\]  

(8)
4. Through-process optimization and application of local loading forming technologies of titanium components

4.1. Optimization and technical identification of isothermal local loading forming of a large-scale TA15 bulkhead

The large-scale integral bulkhead of titanium alloy with thin webs and high ribs is a kind of important structural part in airplanes and it often serves as the key load-bearing structure under severe working conditions. The precise shape together with fine microstructure is required in the isothermal local loading forming of these components. To this end, based on the multi-scale through-process modeling, the comprehensive optimization of forging die, perform billet and processing parameters were conducted according to the idea that (1) avoiding the macro-defects in transitional region through optimal design of block mould, (2) avoiding the underfilling and loading region defects through the preform design, and (3) tailoring the target microstructure and improving performance through optimization of processing parameters. The isothermal local loading forming is carried out on a single-action hydraulic press. The bottom die is kept integral, while the originally integral top die is separated into two parts. A spacer block is implanted between the partial top die and the top die bed to adjust the relative position of the two top dies. The loading region can be changed by adjusting the relative position of the two top dies (Fan et al., 2014). The closed die forging and partition of die along the ribs are employed to reduce the transverse material flow and improve the forming quality of transition region. As for the preform design, the material flow and filling law in the local loading forming of large-scale rib-web component were studied and an analytical model was built to describe the filling law (Zhang and Yang, 2013a; Zhang et al., 2010). By analyzing local loading process characteristic of large-scale bulkhead, it indicates that the simple unequal-thickness billet is suitable for small lot manufacture of these components. Considering the geometry and forming characteristics, such as large dimension, complex shape, mass data, etc., a design method of unequal-thickness billet using analytical analysis and numerical simulation was proposed (Zhang and Yang, 2013b). First, a basic three-dimensional shape of billet was determined by the above analytical models based on local loading features, and then the basic billet was modified according to numerical simulation result considering the local loading forming characteristic. The proper unequal-thickness preform billet which can avoid the forming defects, such as underfilling and folding, was obtained after two modifications, as shown in Fig.10 (a). The processing scheme that near-β forging (T_β-10~20 °C) followed by conventional forging (T_β-30~50 °C) in the last loading pass is preferred to obtain tri-modal microstructure. Based on above optimizations, a large-scale integral TA15 bulkhead with the projection area up to 2.1 m² was successfully formed, as shown in Fig.10 (b). The maximum forming load in local loading step is less than 3000 t, which is much smaller than that in integral forming (about 8000 t). The workpiece exhibits good forming quality with no underfilling and stream line folding. Each loading region and the transitional region all possess the tri-modal microstructure, and the comprehensive mechanical properties of the workpiece satisfy the demands in aircraft domains.

4.2. Optimization and technical identification of heat rotary draw bending of large-diameter thin-walled titanium tube

The large diameter thin-walled (LDTW) titanium bent tubes with small bending radius (R≤2D, R-bending radius, D-outer diameter) is a kind of light-weight component widely used as pneumatic and fuel piping on aircraft. To solve the forming challenges caused by large size factor (D/t>20, t-wall thickness) of tubes and low ductility
and strong anisotropy of material, the heat rotary draw bending method was preferred which can reduce the risk of wrinkling and cracking, and improve the bending formability of LDTW titanium tubes largely. However, the rational working temperature range, heating scheme, die design, and processing parameters should be solved before the heat rotary draw bending comes to industrial application. Therefore, the deformation behavior of (LDTW) titanium tubes at various temperatures and strain rates are investigated experimentally (Zhang et al., 2013c). The thermo-mechanical coupled FE model for heat rotary draw bending was developed, through which the rational working temperature range, heating scheme, die design, and processing parameters were optimized comprehensively (Zhang et al., 2014). Fig.11 shows the heat rotary draw bending equipment and the heat bend LDTW CP-Ti, TC4 and multi-bend TA18 tubes with high forming quality.

Fig. 11. The heat rotary draw bending equipment (a), the heat bend LDTW CP-Ti tubes (b), TC4 tubes (c) and multi-bend TA18 tubes (d) with high forming quality (Zhang et al. 2014).

5. Conclusion

The local loading forming technologies have the potential to form high performance and light weight titanium components (large-scale, integral, complex, thin-walled) widely used in the high-end equipments. By controlling unequal deformation, the local loading forming technologies are capable of reducing forming load, enlarging forming size, improving forming quality and controlling microstructure and performance. Research and development of the local loading forming technologies are not only the requirement for the development of the aero-space, automobile, and high-technology industries, but also the frontiers of plastic forming areas. Developing the multi-scale through-process modeling, unified control techniques of shape forming and microstructure evolution, and through-process processing optimization techniques play a critical role in the development of local loading forming technology. The progresses in these techniques enlarge the application scope of titanium alloys and contribute to the developments in many industry fields.

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