特约专栏

Review on Development of Key Technologies in Plastic Forming of Titanium Alloy

YANG He, WU Chuan, LI Hongwei, FAN Xiaoguang, ZHANG Dawei, JI Zhe
(State Key Laboratory of Solidification Processing, Northwestern Polytechnical University, Xi'an 710072, China)

Abstract: Development of key technologies in plastic forming of titanium alloys is reviewed, focusing on two essentially important aspects, that is, shape forming and microstructure control. Force-saving plastic forming technologies for shape forming are discussed on their applications in manufacturing large-scale complex-shaped titanium components. Some samples of isothermal forming and continuous/intermittent local loading forming of titanium components are presented and discussed. Moreover, springback control and preform optimization are discussed as the important aspects of precision forming technology, and fracture control and underfill control approaches are discussed as aspects of defects control technology as well. In review of microstructure control technologies, mechanism and rules of microstructure evolution, for instance, the evolutions of texture and morphology, are discussed at first, and then several representative numerical modeling approaches, such as internal variables modeling, crystal plasticity modeling and cellular automata modeling, are discussed. In the end, trends, challenges and developments in plastic forming of titanium alloy are presented.

Key words: titanium; isothermal local loading; large-scale complex-shaped component; springback control; preform optimization; internal variables model; crystal plasticity; cellular automata

CLC number: TG146.2^{+}3 **Document code**: A **Article ID**: 1674-3962(2011)06-0006-08

钛合金塑性成形关键技术进展

杨 合，武 川，李宏伟，樊晓光，张大伟，吉 喆
（西北工业大学材料学院 国家凝固重点实验室，陕西 西安 710072）

摘 要：综述了钛合金塑性成形关键技术的发展状况。重点介绍了成形与微观组织演化的研究与发展。在成形方面，主要讨论了省力成形技术在钛合金大型复杂构件成形中的应用，并给出了相关的实例，如钛合金构件的等温成形、连续/间断局部加载成形等；讨论了精确成形技术中的回弹控制与工艺优化等关键问题；在缺陷控制技术方面，主要讨论了如何控制裂纹出现及充填不满等问题；在微观组织演化方面，首先讨论了微观组织的演化机制，如织构与组织形态的演化；其次，讨论了微观组织演化的几种数值建模方法，如内变量法、晶体塑性理论及元胞自动机模型。最后，提出了钛合金构件塑性成形技术领域目前存在的问题与挑战。

关键词：钛合金；等温局部加载；大型复杂构件；回弹控制；工艺优化；内变量法；晶体塑性有限元；元胞自动机

1 Introduction

With the rapid developments in aerospace, especially for the new generation fighter and engine with high comprehensive properties, it is of necessity to introduce the advanced plastic forming technologies to make sure precision, light-weight, high properties and low cost of products. In the field of aerospace, the key components have to possess with excellently mechanical properties, such as room-temperature plasticity and stability in elevated temperatures. Titanium alloy is the suitable candidate due to its advantages of lower density, high specific strength and creep, so that it has been widely used in industries. However, titanium alloys are difficult to form because of their high deformation resistance, low ductility and large anisotropy[1].

Accordingly, various forming approaches such as force-saving and precision forming technologies have been proposed to deal with the difficulties in titanium alloy forming. Among

Received date: 2011-04-21
Roundation item: Natural Science Foundation for Key Program (50935007); Natural Science Foundation (50805121); National Basic Research Program of China (2010CB731701); Foundation for Fundamental Research of Northwestern Polytechnical University in PR China (NPU-FFR-JC20100229); Research Fund of the State Key Laboratory of Solidification Processing of Northwestern Polytechnical University in PR China (27-TZ-2010); the 111 Project (B08040)
Biography: Yang He, Born in 1962, Professor

them, the isothermal local loading forming technology is extensively applied in the aerospace industry since the parts produced by this technology can meet the demand of high performance, lightweight and high reliability. During this forming process, some factors, such as macroscopic and microstructural defects, markedly affect mechanical properties of final products. In order to reduce the influence of these factors on the final properties of components, some efficient methods that have been proposed in the past years are reviewed in the present work.

In this paper, firstly, we discuss the application of force-saving forming technologies in large-scale complex-shaped titanium components. Simultaneously, typical corresponding examples are presented. Secondly, we focus on the springback control and preform optimization approaches related to precision forming technology. In terms of microstructure control technologies, evolving mechanism and some numerical simulation methods are presented in the third part. Finally, trends, challenges and developments in plastic forming of titanium alloy are presented.

2 Developments of key technologies in shape forming of titanium alloy

It is hard for shape-forming of titanium alloy due to its bad formability. Owing to high strength of titanium alloy, huge forming force is required for shape forming, especially for large-scale titanium structure. It commands a high requirement for equipments. Sometimes, the requirement is hard to satisfy. Another aspect, the deeply developed technologies in many industry fields command high-precision requirements on titanium structure without defects. So force-saving plastic forming technology, the precision plastic forming technology, and defects control technology are the key aspects in shape forming of alloy.

2.1 Force-saving plastic forming technologies by improving materials formability and reducing loading area

Due to high strength and high deformation resistance of titanium alloy at room temperature, isothermal forming technology and local loading forming technology are the main force-saving plastic forming technologies through improving material plastic flow and reducing loading area, respectively. Also, the combination of these two technologies was proposed to improve material plastic flow and reduce forcing area simultaneously.

2.1.1 Isothermal forming technology

Isothermal forming technology can effectively raise the metal plasticity and flow properties, improve the homogeneity of metal flow and decrease the deformation pressure [2]. Shan et al. [3] gave the reasons for using isothermal forming technology rather than hot forming technology for manufacturing titanium structure. Titanium alloy is sensitive to deformation temperature, for instance, the deformation resistance of TC4 almost doubles when the deformation temperature falls from 920 to 820 ℃. The deformation pressure of titanium alloy during isothermal forming only accounts for 1/5 to 1/10 in that of hot forging. Due to the low heat conductivity of titanium alloy, deformation and flow velocity inhomogeneity exists between the surface and the interior of the billet in hot forging, which may cause large additional stress and cracking. Furthermore, for complex-shaped titanium parts, large deformation and long operation time are required in shape-forming process, for instance, the Ti-6.5Al-3.5Mo-1.5Zr-0.3Si impeller as illustrated in Fig. 1a. It is mainly machined on a 5 axis-of-freedom NC machining center from a cylindrical billet, which costs more than 1 week, wastes material, and decreases its fatigue life sharply[4]. Aiming at the problems in conventional manufacturing complex-shaped titanium structure, Yang et al. [5] studied the forming process of TC4 blade, as illustrated in Fig. 1 b.

Although isothermal forming technology may improve material formability distinctly, it is a one-step integrated forming technology. It is hard to warrant a good product without any local defects, for instance, under-filling of high ribs or webs. Once a product is formed with defects in local region, even if they are very small, there is no any chance to make them up. This may be the disadvantage lying in this technology.

2.1.2 Local loading forming technology

Continuous local loading forming Continuous local loading forming technology is widely used for manufacturing components with revolution body to save forming force and improve formability, especially in hard-to-form local region, for instance, high ribs or webs. Ring rolling process and spinning process are the typical representations for continuous local loading forming technology.

Hot ring rolling is used in manufacturing large seamless rings of titanium alloy with rectangle- section [6] and special-shaped section[7-9]. However, the process is highly nonlinear with characteristics as 3D continuous incremental deformation, unstable and asymmetrical state, dynamic contact and growth. Thus, how to maintain a steady forming condition is the key issue in this process. Guo et al. [10] proposed a simple and efficient method to determine the dynamic speed boundary condition caused by the guide rolls in finite element (FE) modeling, and then they investigated the plastic deformation behavior in cold radial ring rolling process[11]. This approach achieves good control of guide rolls at most cases, however, loses control sometimes since it applies constraints of displacement on guide rolls according to geometric calculation. In order to control guide rolls flexibly in numerical simulation so as to meet the condition in fact, Li et al. [12] introduced a hydraulic adjustment mechanism in FE modeling. By using the hydraulic adjustment mechanism, Wang et al. [13] simulated hot ring rolling process of TC4 alloy in radial ring rolling process, as illustrated in Fig. 2a, Guo and Yang[14] analyzed the thermal-mechanical modeling approach, flexible control technology of guide rolls and approach for determination of the motions of axial rolls in radial-axial ring rolling process, as illustrated in Fig. 2b.

Different from ring rolling as a bulk forming process, spinning is another typical continuous local loading blank forming process. Spinning of titanium alloy at room temperature is difficult due to high deformation resistance and yield-to-tensile ratio. Thus, the formability of Ti-5523 titanium alloy during spinning was analyzed based on a hot compressive test, and proper power spinning temperature of Ti-5523 titanium alloy is found at about 650 ~ 750 ℃[15]. As a branch of spinning, spin extrusion can produce long rotationally symmetric hollow shapes from solid bar. The spin extrusion process of Ti-10V-2Fe-3Al titanium alloy was investigated by Neugebauer et al. [16], and found the reliable temperature distribution window is between about 500 ~ 600 ℃. Li et al.[17] established a 3D thermo-mechanical coupled FE model for hot power spinning of TA15 titanium alloy thin-walled shell. In order to simulate the moving heat source in fact, the billet in the model was separated into several heating rings and the volumetric heat generation was applied in the heating ring. Moreover, the backward tube spinning of BT20 titanium alloy was investigated by Shan et al.[18] and Yang et al[19].

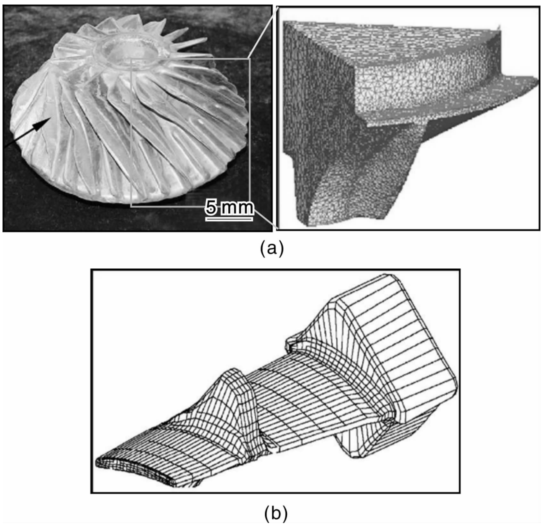

Fig. 1 Large-scale complex-shaped titanium components forming by isothermal forming technology (a) Ti-6.5Al-3.5Mo-1.5Zr-0.3Si impeller and (b) TC4 blade

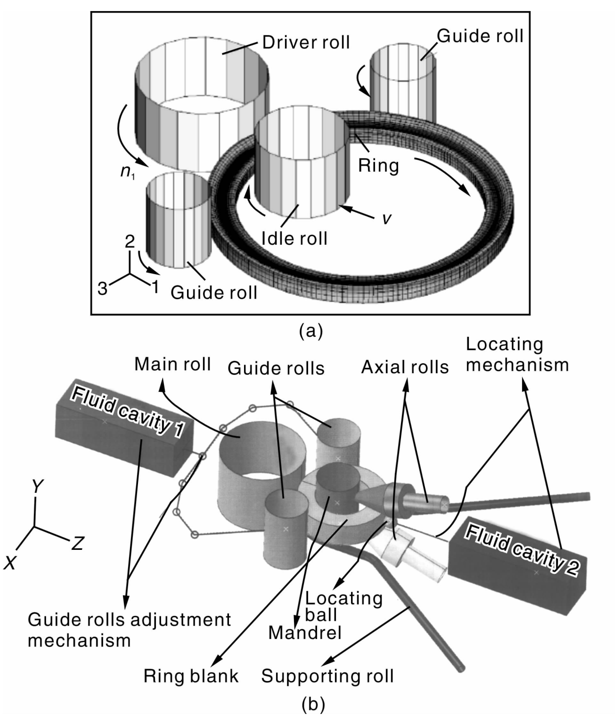

Fig. 2 3D coupled thermo-mechanical FE models for hot ring rolling of titanium alloy: (a) radial ring rolling and (b) radial-axial ring rolling

Intermittent local loading forming Comparing with continuous local loading forming technology, intermittent local loading forming technology is developed to form asymmetric irregular components, for instance, the bulkhead used in aircraft, as illustrated in Fig. 3. This large-scale complex rib-web component of titanium alloy needs enormous force to form by integral forming technology due to its large global size and high ribs and webs in local area, which may exceed the limit of current equipment. In intermittent local loading forming, the upper or lower die is divided into several parts, and only partial die is loaded in one local loading step, as illustrated in Fig. 4. The milestone of this forming technology is the successful manufacture of titanium bulkhead (Fig. 3a) used on F-22 fighter with the weight of 1 590 kg and projected area of 5 m^2 by Wyman-Gordon Co. Limited. Otherwise, more than 1 000 MN press may be required to form this component by integral forming technology.

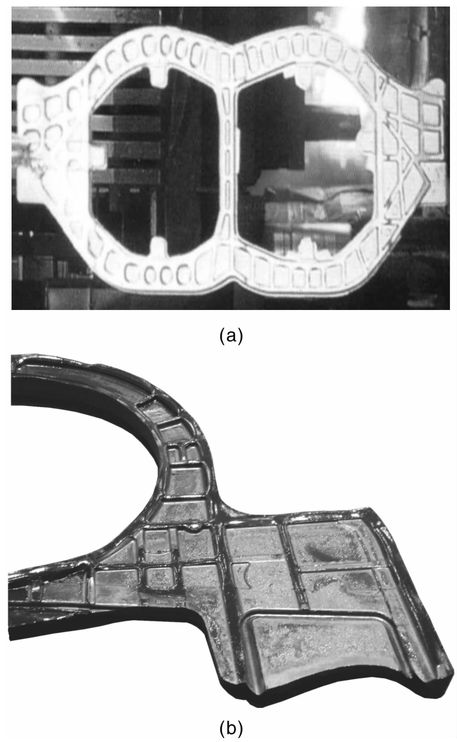

Fig. 3 Bulkhead used in aircraft

Furthermore, Yang et al.[20-24] have done systematic modeling and simulation of the forming of large-scale complex-shaped bulkhead of TA15 titanium alloy, as shown in Fig. 3 b, of which sizes are both greater than 1 000 mm in length and width, by the intermittent local loading combining with isothermal forming. In this isothermal local loading forming process, the maximal load is only about 30 000 kN in local loading steps. Also, they have done many theoretic researches on the rules of the highly nonlinear unequal deformation, the coupling effects of multi-steps, multi-fields and multi-factors, and the defects such as under-filling, flow lines disturbance, folding, etc.

2.2 Precision plastic forming technologies through springback control and preform optimization

Precision plastic forming technology is pushed forward by the development of new high-tech industry, requires minor cycle of production, material saving and cost control.

Net-forming or near net-forming is the main approach to

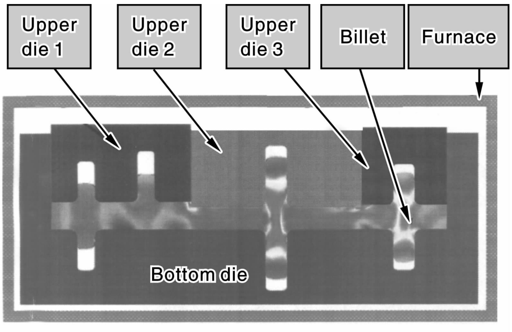

Fig. 4　Schematic of isothermal local loading forming process

achieve precision plastic forming. However, springback of products after forming operation and preform design prior to final operation are two important aspects to influence the precision in plastic forming process. Many works have been done in the fields of springback control and preform design.

2.2.1　Springback control through various criterions

Springback is significant in plastic working on titanium due to the large deformation resistance, low elastic modulus and strong anisotropy of the material. It greatly influences the size and shape errors of the products. Till now, a lot of efforts have been carried out to minimize the forming error caused by springback. Finite element (FE) simulation in combination with optimization techniques is the most applied method. He et al.[25] developed an optimization method to reduce springback in cold stretch forming of TC1 aircraft skin. In the optimization model, a mathematical formulation of stress difference calculated by FEM was developed as an indicator of springback degree instead of implicit springback analysis, and multi-island genetic algorithm was employed to seek the optimal loading parameters. The optimization design of process parameters effectively reduced the amount of springback and improved the shape accuracy. The results provide a guideline for controlling springback in stretch forming of aircraft skin. Jiang et al.[26] established a quantitative relationship among bending angle, material properties and springback angle with multivariate and stepwise analysis based on a self-developed FE model for the numerically controlled (NC) rotary tube bending of a TA18 alloy (Ti-3Al-2.5V). Toussain et al.[27] used the Hill's anisotropic criterion to predict springback during the bending forming process of a commercially pure titanium (CP-Ti) part. Adamus and Lacki[28] suggested that the springback of TC4 bended bar depends on the size of the middle material zone remaining in elastic state, which in turn depends on the processing and geometric parameters, such as bending radius, bending angle and diameter/thickness of the bending element. Torng et al.[29] used statistical method to find the relationship between springback angle and forming parameters in hydro-forming process, which provided an efficient approach for the tooling designer and technician to reduce the manufacturing lead time. Ozturk et al.[30] investigated the effect of warm temperature on springback compensation of CP-Ti sheet. The results reveal that the springback is substantially reduced with increasing temperature.

2.2.2　Approaches on optimization of preform and die

Preform and die optimization can substantially reduce the error in bulk forming, which is of significant importance to near-net shape forming. Backward simulation is widely used in preform design. Gao et al.[31-32] proposed a new backward loading method to optimize the preform of Ti-6Al-4V blades. The method directly uses the backward velocity to calculate in every time step, which can improve computational efficiency without the geometrical searching and iteration. Zhou et al.[33] proposed a stepwise reverse optimization method to optimize the initial billet of TA15 alloy. It is found that the choice of correction surface, which is used to determine optimization object, is the basis of optimization; equidistance offsetting determines the accuracy and reliability of the optimization. In order to achieve net shape forming of titanium aerofoil blades, Ou et al.[34-36] proposed a FE-based simulation approach for the forging process, quantified the forging errors due to die-elastic deformation, thermal distortion and press elasticity, developed a forging simulation and optimization system, and minimized the forging error through die shape optimization.

2.3　Defects-control technologies by improving forming techniques

Defects, such as fracture and under-fill, are prone to occur during forming process of titanium components since they are sensitive to loading conditions, processing parameters and material properties. Solutions have been proposed for defects control in various forming process of titanium components.

2.3.1　Fracture-control approaches

Fracture is prone to occur in the cold forming process of titanium alloys, such as rotary bending of TA18 titanium alloy[37], single point increment forming of pure titanium[38], stretch forming of TC1 titanium alloy[39] and power spinning of Ti-15-3[40]. In single point incremental forming (SPIF) process of CP-Ti sheet, Hussain et al.[38] presented that the thickness along the workpiece decreases as depth increases to avoid fracture in forming process. He et al.[39] pointed out that excessive post-stretch force leads to a fracture risk in cold stretch forming of TC1 titanium alloy. Optimizing the pre-stretch and post-stretch forces can avoid fracture. The experiments of cold power spinning of Ti-15-3 indicated that the fracture may occur where deformation is inhomogeneous, and found that fracture can be avoided by adopting the reduction rate 30% ~40% in the first pass[40].

2.3.2　Underfill-control approaches

Underfill is a typical forming defect in plastic forming of large-scale complex-shaped titanium alloy component, for instance, the bulkhead shown in Fig. 3. In general, in order to eliminate underfill defect, a desirable volume distribution is measured prior to final forging operation. However, complex preform of titanium needs multi-fire forging, even isothermal forging. This will increase the cost, length of the cycle, and coarse grain size. The cavity fill can also be improved by controlling the deformation modes of the billet in final forging operation. For instance, through changing the loading mode, the yielding area mainly occurs in local regions, and the underfill in cavity of impeller blades is avoided[41]. For forming large-scale titanium bulkheads, the filling of rib cavities are effectively improved by using isothermal local loading forming technology combining simple unequal-thickness billet[42-43].

3 Developments of key technologies in microstructure control during forming process of titanium alloy

Microstructure, which is sensitive to processing, does distinct effects on the performance of titanium products. Beyond the precision shape-forming, microstructure control is essentially necessary to ensure an expected performance for titanium alloy forming. To this end, mechanism and rules of microstructure evolution during forming process of titanium alloy have to be made clear at first so that some control approaches can be proposed. Experimental test is the useful and commonly used method in this area. However, data at several separate points (or samples) in experiments cannot provide a comprehensive understand of the mechanism and rules of microstructure evolution. Thus, various modeling approaches were proposed to predict microstructure evolution in morphology, topology, texture, phase transformation, recrystallization, grain size distribution, and so on.

3.1 Mechanism and rules of microstructure evolution during forming process of titanium alloy

Texture evolution in meso-scale and morphology evolution in micro-scale are the main aspects should be focused on. How do they evolve, how do they affect product performance, and what are the rules, are the key issues to response.

3.1.1 Mechanism and rules in texture evolution

The crystallographic textures of titanium alloys are formed owing to grain orientation rotation by the continuous dislocation slips or twins in deformation. The evolution of deformation textures is strongly sensitive to strain, temperature and deformation modes[44], which influences the subsequently microstructural evolution and corresponding mechanical properties of titanium alloys, such as strength, fatigue life, corrosion resistance[45-47]. Therefore, the texture can be controlled through proper plastic working[1]. The deformation texture is usually formed during the cold forming process, which is influenced by alloy compositions, initial texture and processing parameters. Germain et al.[48-49] studied the development of sharp local texture of IMI834 alloy and found that this type of texture could essentially reduce the fatigue life. Zeng et al.[50] carried out series of compression tests to study the deformation texture evolution of CP-Ti at high temperatures. They found that the basal planes of both fine and coarse grains in the deformed samples tended to rotate from the initial orientations to an inclination of 45°. Raghunathan et al.[51] investigated the influence of strains on texture evolution of Ti-10V-2Fe-3Al. They observed that the initial beta phase texture keeps evolving at small strains, while the alpha texture could be obtained at large deformation. Moreover, texture may be formed by recrystallization, which is called recrystallized texture. Bozzolo et al.[52-53] found that the changes of texture evolution of CP-Ti during recrystallization resulted from secondary recrystallization. Sander et al.[54] investigated the evolution of recrystallized texture of a Ti-35Nb-7Zr-5Ta alloy during warm rolling. They observed gradient textures when the thickness reduced above 90%. They considered that the dynamic recrystallization caused by the seriously uneven deformation between the surface and the center induced this type of texture.

3.1.2 Mechanism and rules in morphology evolution

Microstructural morphology is sensitive to the processing parameters such as temperature, strain, strain rate, strain path, and heat treatment route[1]. Equiaxed microstructure, basket microstructure, Widmanstaten and their combination are the typical morphologies heavily influencing mechanical properties of titanium alloys. The volume fraction, grain size, aspect ratio directly determine the microstructural morphology of titanium alloys[55-58]. Various titanium alloys with equiaxed morphology containing more than 50% primary alpha phase and the transformed beta phase shows excellently comprehensive properties, so that they have been widely used in many fields of aerospace, chemical processing, marine and offshore, transportation and medicine, etc. Also, the duration and strength of basket microstructure are superior to those of equiaxed microstructure, while its fatigue property is poor. The mechanical properties of Widmanstaten microstructure, such as fracture toughness, duration and creep strength, are excellent due to the large grain size of beta phase and integral alpha interface, which results in extending tortuous contrail dispersing the stress field around fractures. However, the coarsening of beta grain easily takes place because of lack of constraint of alpha phase, which could result in the inferiority of tensile properties. Recently, Zhou et al.[59] obtained a new tri-modal microstructure consists of about 15% equiaxed alpha, 50% ~60% lamellar alpha and transformed beta matrix, which shows a high low cycle fatigue property, high creep-fatigue interactionlife, high fracture toughness and high service temperature, by self-proposed near-beta (about 15 ℃ below the beta transus) forging process. Fan et al.[60] investigated the effect of strain distribution on the microstructural morphology of large-scale component of TA15 titanium alloy under near beta local loading forming. They found that the microstructural morphology of TA15 titanium alloy varied with the deformation degree and processing steps. Transformed beta particles with primary alpha and lamellar alpha phase were produced by small deformation regardless of processing steps. While the aggregated transformed beta matrix with disordered lamellar alpha phases was produced by large deformation in the first step. In the second step, microstructural morphology with transformed beta matrix and partly and fully globularized secondary alpha phases was produced by moderate and large deformation, respectively.

3.2 Developments of modeling approaches

The typical modeling approaches for microstructure evolution prediction are the statistical modeling, physical-based modeling and microscopic modeling, for instance, internal variables modeling, crystal plasticity modeling and cellular automata modeling. Since each approach is a set of integrated theory, only several key points in these approaches are discussed as following.

3.2.1 Internal variables model

The internal state variable methods, which describe the underlying phenomena in terms of a small number of internal state variables, have been widely used to model the microstructure evolution in hot working of titanium alloys. Luo et al.[61] proposed a physically based constitutive model to predict the flow stress and grain size variation of two-phase titanium alloys. In the constitutive model, the total stress is assumed to be composed of a thermally activated stress and an athermal stress, in which the thermally activated stress is described by a Kock-Mecking model. The athermal stress associated with the hardening effect is represented by two-parameter internal state variables, including the dislocation density rate and the grain size rate. The role of the alpha phase and beta phase on the flow stress is characterized with the rule of mixture and superposition theory. Predictions of the model are in good agreement with the experimental results of a Ti-6Al-4V alloy. A similar model has also been proposed by Li et al. [62] for the two-phase TC6 alloy. Sun et al. [63] proposed a model to predict the grain size variation of equiaxed alpha phase during hot working of a TA15 alloy based on the evolution of two internal state variables: dislocation density and recrystallized fraction.

3.2.2　Crystal plasticity model

Crystal plasticity model can reflect the physical-based mechanisms, such as microscopic slipping and twinning, inhomogeneous deformation in micro-scale, variant deformation resistance of microstructures, evolution of orientations, so that is deeply developed and widely used. In this theory, rate independent crystal plasticity (RICP) and rate dependent crystal plasticity (RDCP) were proposed and developed, respectively. The main problems lying in the numeralization of RICP is the non-uniqueness of active slip systems during the plastic deformation of a single crystal and the determination of time-independent shearing rates[64]. McGinty and McDowell[65] introduced a semi-implicit integration scheme to identify active slip systems prior to determining their shearing rates, and to quantify the order in which slip system become active. The problem, caused by RICP model, is overcome in the RDCP model by assuming that all slip systems are always active. However, severe numerical instability arises in the integration of the RDCP model due to the high-order nonlinear flow rule. Implicit algorithms for solving RDCP model were proved with good stability on solution, see the works of Kalidindi and Anand[66], Cuitiño and Ortiz[67], Sarma and Zacharia[68], Mcginty[69], and Li et al[64]. However, these schemes involve iterations both at the local level to update the stress and globally to enforce equilibrium, requiring thus much computational effort[70], so that it almost cannot be applied in simulation of 3D forming process with thousands of elements. Therefore, Li et al. [71] proposed an explicit algorithm to improve the computational effeciency. Their work is proved efficient, but should be improved further to apply it to large deformation and complex loading conditions. Another problem should be handled when this theory is applied to titanium alloy. Owing to the HCP structure of titanium alloy, slipping is the main deformation mode for α and β phase, while twinning is the optional mode for α phase. There exists several methods to handle the problem of extremely large number of new orientations created by deformation twinning, such as predominant twin reorientation (PTR) method [72], volume fraction transfer (VFT) approach[73], and total lagrangian approach[74]. Roters et al. [75] reviewed this theory on the modeling approach, problem-handling approach, and its applications in more details.

3.2.3 Cellular automata model

Cellular automata (CA) algorithm has been widely used to model microstructural evolution phenomena, e. g. dynamic recrystallization, static recrystallization, grain coarsening. Ding and Guo[76-78] combined CA model with principles of DRX to simulate microstructural evolution of TC4 alloy in alpha plus beta and beta fields. They introduced the variation of dislocation density calculated from K-M model as internal state to link meso-structural features with actual processing conditions. In their CA model, the important phenomena, such as the nucleation rate, growth kinetics, and the effects of processing parameters, as well as the initial grain size, had been taken into account, which enabled both quantitative and topographic simulations of the growth kinetics and topology of each R-grain during microstructure evolution. The predicted results in terms of shapes of flow stress-strain curve, growth behavior of R-grains and final microstructure morphology closely resembled experimental findings. Chun et al. [79] modeled the static recrystallization of purity titanium during cooling process through CA approach. They found that factors, such as uneven deformation, heterogeneous nucleation, can result in a deviation of recrystallization kinetics from experimental observations. To introduce inhomogeneous deformation gradient to each grain during deformation in micro-scale, Raabe et al. [80] simulated microstructural evolution by coupling CA model with crystal plasticity finite element method (CPFEM).

4　Remarks

An outlook on the key technologies in plastic forming of titanium alloy is taken here. There are 4 trends: efficient and saving precision plastic forming; plastic forming of integrated large-scale components combing with extremely small characters; near net-forming of lightweight high-performance structures; numerical plastic forming based on multiscale modeling and simulation, 3 challenges: forming large-scale integrated components through local loading forming technology; integrated control of inhomogeneous deformation and microstructure evolution; optimization and robust control of forming process based on multiscale modeling and simulation, and 4 developments in near net-forming of large-scale or complex structures: large-scale complex-shaped integrated titanium bulkhead produced by isothermal local loading forming technology; large-scale complex-shaped ring rolling technology; large-scale complex-shaped thin-walled shell spinning technology; precision NC bending technology of large-radius thin-walled tubes.

References

[1] Yang H, Fan X G, Sun Z C, *et al.* Recent Developments in Plastic Forming Technology of Titanium Alloys [J]. *Sci China Tech Sci*, 2011, 54: 490-501.

[2] Rusz S, Sinczak J, Lapkowski W. Isothermal Plastic Forming of High-Carbon Steel[J]. *Mate Sci En A*, 1997, 234-236: 430-433.

[3] Shan D B, Xu W C, Lu Y. Study on Precision Forging Technology for a Complex-Shaped Light Alloy Forging [J]. *J Mater Process Technol*, 2004, 151: 289-293.

[4] Shi K, Shan D B, Xu W C, *et al.* Near Net Shape Forming of a Titanium Alloy Impeller [J]. *Journal of Materials Processing Technology*, 2007, 187-188: 582-585.

[5] Yang H, Zhan M, Liu Y L. A 3D Rigid-Viscoplastic FEM Simulation of the Isothermal Precision Forging of a Blade with a Damper

Platform[J]. *Journal of Materials Processing Technology*, 2002, 122: 45 -50.

[6] Yang H, Wang M, Guo L G, *et al*. 3D Coupled Thermo-Mechanical FE Modeling of Blank Size Effects on the Uniformity of Strain and Temperature Distributions during Hot Rolling of Titanium Alloy Large Ring [J]. *Computational Materials Science*, 2008, 44: 611 -621.

[7] Yang D Y, Kim K H, Hawkyard J B. Simulation of T-Section Profile Ring Rolling by the 3-D Rigid-Plastic Finite Element Method [J]. *International Journal of Mechanical Science*, 1991, 33 (7): 541 -550.

[8] Li L Y, Yang H, Guo L G , *et al*. Research on Interactive Influence of Parameters on T-Shaped Cold Ring Rolling by 3d-FE Numerical Simulation [J]. *Journal of Mechanical Science and Technology*, 2007, 21(10): 1 541 -1 547.

[9] Hua L, Qian D S, Pan L B. Deformation Behavior and Conditions in L-Section Profile Cold Ring Rolling[J]. *Journal of Materials Processing Technology*, 2009, 209(11): 5 087 -5 096.

[10] Guo L G, Yang H, Zhan M, *et al*. Simulation for Guide Roll in 3D-FE Analysis of Cold Ring Rolling [J]. *Material Science Forum*, 2004, 471 -472: 760 -764.

[11] Guo L G, Yang H, Zhan M. Research on Plastic Deformation Behaviour in Cold Ring Rolling by FEM Numerical Simulation [J]. *Modelling and Simulation in Materials Science and Engineering*, 2005, 13(7): 1 029 -1 046.

[12] Li L Y, Yang H, Guo L G, *et al*. A Control Method of Guide Rolls in 3D-FE Simulation of Ring Rolling [J]. *Journal of Material Processing Technology*, 2008, 205(1 -3): 99 -110.

[13] Wang M, Yang M, Sun Z C, *et al*. Analysis of Coupled Mechanical and Thermal Behaviors in Hot Ring Rolling of Large Rings of Titanium Alloy Using 3D Dynamic Explicit FEM [J]. *Journal of Materials Processing Technology*, 2009, 209 (7): 3 384 -3 395.

[14] Guo L G, Yang H. Key Technologies for 3D-FE Modeling of Radial-Axial Ring Rolling Process [J]. *Materials Science Forum*, 2008, 575 -578: 367 -372.

[15] Mao B P, Wang F C, Zhao Y H, *et al*. Study on Spinning Properties of Titanium Alloy [J]. *Chinese Journal of Rare Metals*, 2004, 28(1): 271 -273.

[16] Reimund N, Lothar W M Thorsten H, *et al*. Manufacture of a β-Titanium Hollow Shaft by Incremental Forming [J]. *Production Engineering*, 2010. DOI: 10.1007/s11740 -010 -0280 -z.

[17] Li H, Zhan M, Yang H, *et al*. Couple Thermal-Mechanical FEM Analysis of Power Spinning of Titanium Alloy Thin-Walled Shell [J]. *Chinese Journal of mechanical Engineering*, 2008, 44(6): 187 -193.

[18] Shan D B, Yang G P, Xu W C. Deformation History and the Resultant Microstructure and Texture in Backward Tub Spinning of Ti-6Al-2Zr-1Mo-1V [J]. *Journal of Materials Processing Technology*, 2009(209): 5 713 -5 719.

[19] Yang G P, Xu W C, Chen Y, *et al*. Research on Material Flow Rule of Backward Tube Spinning Process[J]. *Journal of Plasticity Engineering*, 2008, 15(6): 48 -52.

[20] Wu Y J, Yang H, Sun Z C, *et al*. Simulation on Influence of Local Loading Conditions on Material Flow During Rib-Web Components Forming [J]. *China Mechanical Engineering*, 2006, 17(Special): 12 -15.

[21] Li Z Y, Yang H, Sun Z C, *et al*. Research on Marco-Microcosmic Deforming in Isothermal Local Loading Transition Region for Large-Scale Complex Integral Components of TA15 Titanium alloy[J]. *Rare Metal Materials and Engineering*, 2008, 37 (9): 1 516 -1 521.

[22] Zhang D W, Yang H , Sun Z C. Analysis of Local Loading Forming for Titanium-Alloy T-Shaped Components Using Slab Method [J]. *Journal of Materials Processing Technology*, 2010, 210: 258 -266.

[23] Sun Z C, Yang H. Mechanism of Unequal Deformation During Large-Scale Complex Integral Component Isothermal Local Loading Forming[J]. *Steel Research Int*, 2008, 79(Special Edition 1): 601 -608.

[24] Sun N G, Yang H, Sun Z C . Optimization on the Process of Large Titanium Bulkhead Isothermal Closed-Die Forging [J]. *Rare Metal Materials and Engineering*, 2009, 38(7): 1 296 -1 300.

[25] He D H, Li D S, Li X Q, *et al*. Optimization on Springback Reduction in Cold Stretch Forming of Titanium-Alloy Aircraft Skin [J]. *Trans Nonferrous Met Soc China*, 2010, 20: 2 350 -2 357.

[26] Jiang Z Q, Yang H, Zhan M, *et al*. Coupling Effects of Material Properties and the Bending Angle on the Springback Angle of a Titanium Alloy Tube During Numerically Controlled Bending [J]. *Mater Design*, 2010, 31(4): 2 001 -2 010.

[27] Toussaint F, Tabourot L, Ducher F. Experimental and Numerical Analysis of the Forming Process of a CP Titanium Scoliotic Instrumentation [J]. *J Mater Process Technol*, 2008, 197(1 -3): 10 -16.

[28] Adamus J, Lacki P. Forming of the Titanium Elements by Bending [J]. *Comput Mater Sci*, 2011, 50(4): 1 305 -1 309.

[29] Torng C, Huang C, Chang H M. Springback Analysis of Ti-6Al-4V in Hydro-Forming Process for Aerospace Sheet Metal Parts [J]. *Steel Res Int*, 2008. (Special Issue 1): 288 -292.

[30] Ozturk F, Ece R E, Polat N, *et al*. Effect of Warm Temperature on Springback Compensation of Titanium Sheet[J]. *Mater Manuf Process*, 2010(25): 1 021 -1 024.

[31] Gao T, Yang H, Liu Y L. Influence of Dynamic Boundary Conditions on Preform Design for Deformation Uniformity in Backward Simulation[J]. *J Mater Process Technol*, 2008, 197 (1 -3): 255 -260.

[32] Gao T, Yang H, Liu Y L. Backward Tracing Simulation of Precision Forging Process for Blade Based on 3D FEM[J]. *Trans Nonferrous Met Soc China*, 2006, 16(2): 639 -644.

[33] Zhou W J. *Initial Billet Optimization and Process Parameters Determination in Preforming of TA15 Titanium Alloy Large and Complex Components*[R]. Xi'an: Northwestern Polytechnical University. 2010.

[34] Ou H, Armstrong C. Evaluating the Effect of Press and Die Elasticity in Forging of Aerofoil Sections Using Finite Element Simulation [J]. *Finite Elem Anal Des*, 2006, 42 (10): 856 -867.

[35] Ou H, Armstrong C, Price M. Die Shape Optimisation in Forging of Aerofoil Sections[J]. *J Mater Process Technol*, 2003, 132(1 -3): 21 -27.

[36] Ou H, Armstrong C. Die Shape Compensation in Hot Forging of Titanium Aerofoil Sections [J]. *J Mater Process Technol*, 2002, 125 -126: 347 -352.

[37] Jiang Z Q, Yang H, Zhan M, *et al*. Establishment of a 3D FE Model for the Bending of Titanium Alloy Tube [J]. *International Journal of Mechanical Sciences*, 2010, 52(9): 1 115 -1 124.

[38] Hussain G, Gao L, Zhang Z Y. Formability Evaluation of a Pure Titanium Sheet in Cold Increment Forming Process[J]. *International Journal of Advanced Manufacturing Technology*, 2008, 37: 920 -926.

[39] He D H, Li D S, Li X Q, *et al*. Optimization on Springback Reduction in Cold Stretch Forming of Titanium-Alloy Aircraft Skin [J]. *Transactions of Nonferrous Metals Society of China*, 2010, 20: 2 350 -2 357.

[40] Shan D B, Tong W Z, Xu Y, *et al*. Effects of Plastic Deformation Inhomogeneity on Process of Cold Power Spinning of Ti-15 -3 [J]. *The Chinese Journal of Nonferrous Metals*. 2000, 10 (6): 887 -890.

[41] Shi K, Shan D B, Xu W C, *et al*. Near Net Shape Forming of a Titanium Alloy Impeller [J]. *Journal of Materials Processing Technology*, 2007, 187 -188: 582 -585.

[42] Sun N G, Yang H, Sun Z C. Optimization on the Process of Large Titanium Bulkhead Isothermal Closed-Die Forging [J]. *Rare Metal Materials and Engineering*. 2009, 38(7): 1 296 -1 300.

[43] Sun Z C, Yang H. Forming Quality of Titanium Alloy Large-Scale Integral Components Isothermal Local Loading [J]. *The Arabian Journal for Science and Engineering*, 2009, 34(10): 35 – 45.

[44] Leyens C, Peters M. *Titanium and Titanium Alloys* [M]. Weinheim: Wiley-VCH, 2003.

[45] Bache M R, Evans W J. Impact of Texture on Mechanical Properties in an Advanced Titanium Alloy [J]. *Mater Sci Eng A*, 2001, 319 – 321: 409 – 414.

[46] Whittaker M T, Evans W J, Lancaster R, *et al*. The Effect of Microstructure and Texture on Mechanical Properties of Ti6 – 4 [J]. *Int J Fatigue*, 2009, 31(11 – 12): 2 022 – 2 030.

[47] Evans W J, Jones J P, Whittaker M T. Texture Effects under Tension and Torsion Loading Conditions in Titanium Alloys [J]. *Int J Fatigue*, 2005, 27(10 – 12): 1 244 – 1 250.

[48] Germain L, Gey N, Humbert M, *et al*. Analysis of Sharp Microtexture Heterogeneities in a Bimodal IMI 834 Billet[J]. *Acta Mater*, 2005, 53(13): 3 535 – 3 543.

[49] Germain L, Gey N, Humbert M, *et al*. Texture Heterogeneities Induced by Subtransus Processing of Near Titanium Alloys [J]. *Acta Mater*, 2008, 56(16): 4 298 – 4 308.

[50] Zeng Z, Zhang Y, Jonsson S. Microstructure and Texture Evolution of Commercial Pure Titanium Deformed at Elevated Temperatures [J]. *Mater Sci Eng A*, 2009, 513 – 514: 83 – 90.

[51] Raghunathan S L, Dashwood R J, Jackson M, *et al*. The Evolution of Microtexture and Macrotexture during Subtransus Forging of Ti-10V-2Fe-3Al[J]. *Mater Sci Eng A*, 2008, 488(1 – 2): 8 – 15.

[52] Bozzolo N, Dewobroto N, Grosdidier T, *et al*. Texture Evolution during Grain Growth in Recrystallized Commercially Pure Titanium[J]. *Mater Sci Eng A*, 2005, 397(1 – 2): 346 – 355.

[53] Wagner F, Bozzolo N, Landuyt O, *et al*. Evolution of Recrystallisation Texture and Microstructure in Low Alloyed Titanium Sheets[J]. *Acta Mater*, 2002, 50(5): 1 245 – 1 259.

[54] Sander B, Raabe D. Texture inhomogeneity in a Ti-Nb-Based β-Titanium Alloy After Warm Rolling and Recrystallization [J]. *Mater Sci Eng A*, 2008, 479(1 – 2): 236 – 247.

[55] Luo J, Li M, Yu W, *et al*. Effect of the Strain on Processing Maps of Titanium Alloys in Isothermal Compression [J]. *Mater Sci Eng A*, 2009, 504(1 – 2): 90 – 98.

[56] Jones N, Dashwood R, Dye D, *et al*. Thermomechanical Processing of Ti-5Al-5Mo-5V-3Cr [J]. *Mater Sci Eng A*, 2008, 490(1 – 2): 369 – 377.

[57] Zong Y Y, Shan D B, Lu Y. Microstructural Evolution of a Ti-4.5Al-3Mo-1V Alloy during Hot Working [J]. *J Mater Sci*, 2006, 41(12): 3 753 – 3 760.

[58] Wang K, Zeng W, Zhao Y, *et al*. Dynamic Globularization Kinetics during Hot Working of Ti-17 Alloy with Initial Lamellar Microstructure[J]. *Mater Sci Eng A*, 2010, 527(10 – 11): 2 559 – 2 566.

[59] Zhou Y G, Zeng W D, Yu H Q. An Investigation of a New Near-Beta Forging Process for Titanium Alloys and Its Application in Aviation Components[J]. *Materials Science and Engineering A*, 2005, 393(1 – 2): 204 – 212.

[60] Fan X G, Sun Z C, Zhang D W. Effect of Deformation Inhomogeneity on the Microstructure and Mechanical Properties of Large-Scale Rib-Web Component of Titanium Alloy under Local Loading Forming[J]. *Mate Sci Eng A*, 2010, 527: 5 391 – 5 399.

[61] Luo J, Li M, Li X, *et al*. Constitutive Model for High Temperature Deformation of Titanium Alloys Using Internal State Variables [J]. *Mech Mater*, 2010, 42(2): 157 – 165.

[62] Li X, Li M. A Set of Microstructure-Based Constitutive Equations in Hot Forming of a Titanium alloy [J]. *J Univ Sci Technol B*, 2006, 13(5): 435 – 441.

[63] Sun Z, Yang H, Han G, *et al*. A Numerical Model Based on Internal-State-Variable Method for the Microstructure Evolution during Hot-Working Process of TA15 Titanium Alloy[J]. *Mater Sci Eng A*, 2010, 527(15): 3 464 – 3 471.

[64] Li H W, Yang H, Sun Z C. A Robust Integration Algorithm for Implementing Rate Dependent Crystal Plasticity into Explicit Finite Element Method [J]. *Int J Plasticity*, 2008, 24(2): 267 – 288.

[65] McGinty R D, McDowell D L. A Semi-Implicit Integration Scheme for Rate Independent Finite Crystal Plasticity[J]. *International Journal of Plasticity*, 2006, 22 (6): 996 – 1 025.

[66] Kalidindi S R, Anand L. An Approximate Procedure for Predicting the Evolution of Crystallographic Texture in Bulk Deformation Processing of fcc Metals [J]. *Int J Mech Sci*, 1992, 34(4): 309 – 329.

[67] Cuitiño A M, Ortiz M. Computational Modelling of Single Crystals [J]. *Modelling and Simulation in Materials Science and Engineering*, 1992(1): 225 – 263.

[68] Sarma G, Zacharia T. Integration Algorithm for Modeling the Elasto-Viscoplastic Response of Polycrystalline Materials [J]. *Journal of Mechanics and Physics of Solids*, 1999, 47(6): 1 219 – 1 238.

[69] McGinty R D. *Crystallographic Multiscale Representation of Polycrystalline Inelasticity* [D]. Atlanta: Georgia Institute of Technology, 2004.

[70] Raphanel J L, Ravichandran G, Leroy Y M. Three-Dimensional Rate-Dependent Crystal Plasticity Based on Runge-Kutta Algorithms for Update and Consistent Linearization[J]. *Int J Plasticity*, 2004, 41(22 – 23): 5 995 – 6 021.

[71] Li H W, Yang H, Sun Z C. Explicit Incremental-Update Algorithm for Modeling Crystal Elasto-Viscoplastic Response in Finite Element Simulation[J]. *Transactions of Nonferrous Metals Society of China*, 2006b, 16 (Sp1): s624 – s630.

[72] Houtte P V. Simulation of the Rolling and Shear Texture of Brass by the Taylor Theory Adapted for Mechanical Twinning[J]. *Acta Metall Mater*, 1978, 26: 591 – 604.

[73] Tome C N, R. Lebensohn A, Kocks U F. A Model for Texture Development Dominated by Deformation Twinning: Application to Zirconium Alloys[J]. *Acta Metall Mater*, 1991, 39: 2 667 – 2 680.

[74] Kalidindi S R. Incorporation of Deformation Twinning in Crystal Plasticity Models [J]. *J Mech Phys Solids*, 1998, 46: 267 – 290.

[75] Roters F, Eisenlohr P, Hantcherli L, *et al*. Overview of Constitutive Laws, Kinematics, Homogeneous and Multiscale Methods in Crystal Plasticity Finite-Element Modeling: Theory, Experiments, Applications [J]. *Acta Materialia*, 2010, 58: 1 152 – 1 211.

[76] Ding R, Guo Z X. Microstructural Evolution of a Ti-6Al-4V Alloy during Phase Processing: Experimental and Simulative Investigations[J]. *Mater Sci Tech*, 2004, A365: 172 – 179.

[77] Ding R, Guo Z X. Coupled Quantitative Simulation of Microstructure Evolution and Plastic Flow during Dynamic Recrystallization[J]. *Acta Mater*, 2001, 49: 3 163 – 3 175.

[78] Ding R, Guo Z X. Microstructural Modeling of Dynamic Recrystallization Using an Extended Cellular Automaton Approach[J]. *Comput Mater Sci*, 2002, 23: 209 – 218.

[79] Chun Y B, Semiatin S L, Hwang S K. Monte Carlo Modeling of Microstructure Evolution during the Static Recrystallization of Cold-Rolled, Commercial-Purity Titanium [J]. *Acta Mater*, 2006, 54: 3 673 – 3 689.

[80] Raabe D, Becker R C. Coupling of a Crystal Plasticity Finite-Element Model with a Probabilistic Cellular Automaton for Simulating Primary Static Recrystallization in Aluminum[J]. *Model Simul Mater Sci Eng*, 2000, 8: 445 – 462.