Available online at www.sciencedirect.com
ScienceDirect
Trans. Nonferrous Met. Soc. China 25(2015) 1732−1743
Transactions of Nonferrous Metals Society of China
www.tnmsc.cn

Review on hot spinning for difficult-to-deform lightweight metals

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Received 19 August 2014; accepted 20 October 2014

Abstract: Hot spinning process has attracted significant attention because it can be used to manufacture complex parts, extend the forming limit of materials, decrease forming forces and reduce process chains. In this paper, we review researches on lightweight metals spun at elevated temperatures since they are difficult to deform at room temperature. These metals include light alloys, such as titanium, magnesium and aluminum alloys, and metal composites. Then, the heating methods used in the hot spinning process and the treatment methods employed for the temperature boundary condition in finite element analyses for the process were discussed. Finally, the future development directions for the hot spinning process of lightweight but difficult-to-deform alloys were highlighted.

Key words: hot spinning; lightweight metal; heating method; temperature boundary condition; future development direction

1 Introduction

Metal spinning refers to a type of forming process that allows for the production of hollow, mainly axisymmetric components. These components are used widely in the aviation, aerospace, weapons and automobile industries as items such as the supporting cones of jet motors, turboshafts, tailing spouts, the nose cones of rocket engines, the end plates of oil pockets and the connecting rods of automobiles [1−5], as shown in Fig. 1. In recent years, there is an increasing demand for structural components with high strength, light weight and good corrosion resistance to meet the requirements for faster flight speed, longer voyages and lifetimes. Therefore, light metals with the above properties such as titanium alloys, magnesium alloys, aluminum alloys and metal composites have been used more and more widely. Because of the high resistance to deformation and limited ductility at room temperature while large deformation is required, these metals usually have to be formed by heating to specific temperatures to improve their spinnability, decrease forming forces, and reduce process chains [6−8].

Several reviews on spinning have been published in recent years. XIA and XIAO [9] reviewed the novel spinning processes that were used to manufacture complex geometry parts which include non-axisymmetrical spinning, non-circular cross-section spinning, and tooth-shaped spinning. MUSIC et al [10] conducted a thorough survey of academic work on the analysis and application of spinning mechanics and proposed several gaps in the current knowledge of spinning mechanics. WONG et al [11] reviewed the process details of spinning and described developments in terms of researches and industrial applications as well as directions in researches and development for future industrial applications. NEUGEBAUER et al [12] provided an overview on research activities in the field of forming operations at elevated temperatures. JESWIET et al [13] reviewed the progress of metal forming since 2000, including microforming, single-point forming and sheet forming process such as hot spinning. YANG et al [14] reviewed the forming techniques including spinning, used for large-scale integral complex components of titanium alloys. WANG et al [15] introduced the spinning forming of AZ31 and AZ31B magnesium alloys in Japan before 2008. However, none of these reviews focused on the hot spinning of difficult-to-deform lightweight metals.

Because of its many advantages, hot spinning technique has been studied quite extensively on various

Foundation item: Project (51222509) supported by the National Science Fund for Excellent Young Scholars of China; Project (51175429) supported by the National Natural Science Foundation of China; Projects (97-QZ-2014, 90-QP-2013) supported by the Research Fund of the State Key Laboratory of Solidification Processing (NWPU) of China
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DOI: 10.1016/S1003-6326(15)63778-5

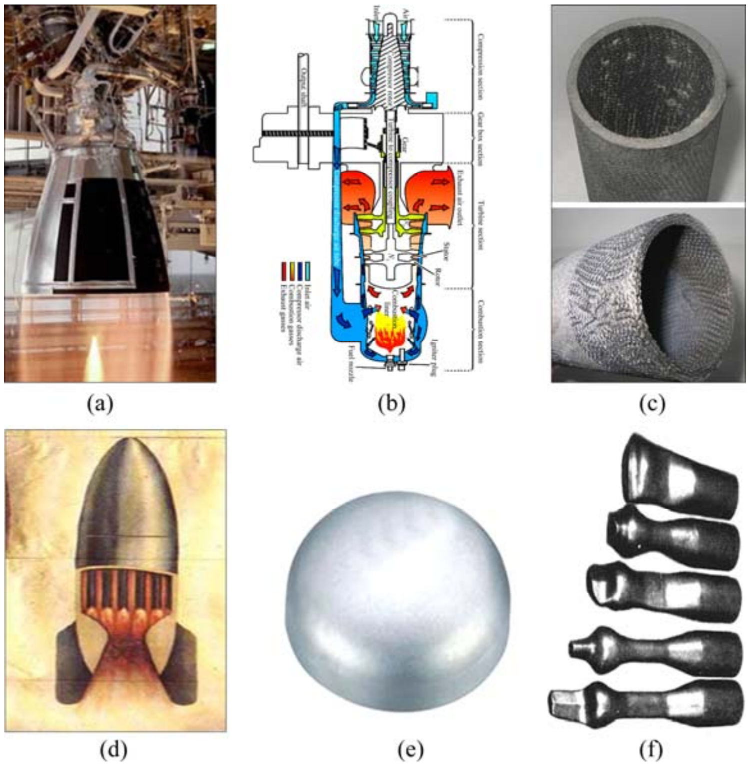

Fig. 1 Spun components used in aviation, aerospace, weapon and automobile industries: (a) Supporting cone of jet motors; (b) Turbo-shaft; (c) Tailing spout; (d) Nose cone of rocket engines; (e) End plate of oil pockets; (f) Connecting rod of automobiles [1−5]

lightweight materials. One of the key techniques in hot spinning of lightweight materials is temperature control, and different materials have different temperature requirements due to their different properties. The control for spinning temperature is closely related to the heating methods used in practical spinning process. And this control in the finite element analysis (FEA) for hot spinning process is the treatment method for temperature boundary conditions in the process. So, in this work, the hot spinning technique by considering the lightweight workpiece materials and the heating methods used in practical spinning processes, and the treatment methods employed for the temperature boundary condition in the finite element analysis (FEA) related to hot spinning were reviewed.

2 Lightweight workpiece materials

The lightweight workpiece materials used for hot spinning in recent years include mainly light alloys such as titanium, magnesium and aluminum alloys and metal composites.

2.1 Titanium alloys

Titanium alloys are advanced materials with high specific strength, excellent heat resistance and corrosion resistance. They have been widely used in the aerospace, aviation, marine and chemical engineering fields [16−18]. There are three types of titanium alloys, including near-alpha titanium alloys, alpha-beta titanium alloys, and metastable beta titanium alloys.

2.1.1 Near-alpha titanium alloys

Near-alpha titanium alloys are of medium or low strength, excellent notch ductility, high temperature creep, good weldability and thermal stability. They include TA12, TA15 (BT20 in Russia), TC1 and TC2. Many researches have been conducted on these alloys, especially on TA15.

LI et al [19] established a three-dimensional (3D) elastic-plastic macro FE model coupled with the thermal-mechanical effect for the hot shear spinning process of a TA15 thin-walled cone. Using this model, ZHAN et al [20−22] investigated the distribution and variation features of temperature, microstructure, stress and strain fields, as well as the influence of process parameters on the process. They found that the effects of contact heat exchange and friction heat can cause a large temperature gradient along the thickness direction of the cone, which can result in remarkable inhomogeneous deformation. They also obtained significant factors on the difference in wall thickness, the fittability of the workpiece with the mandrel and the wrinkling trend.

HUANG and ZENG [23] established a 3D elastic–plastic coupled thermo-mechanical FE model of hot splitting spinning of TA15 titanium alloy. With this model, they found that the variation of the steady-state stress is sharp when strain rate is high while the temperature distributions of circumferential direction of disk blank are even. Besides this, the maximum value of equivalent stress is presented in fillet part. CHEN and KANG [24] established a 3D rigid-plastic macro FE model coupled with the thermal-mechanical effect for the hot flow spinning of a BT20 tube. By using this model, they found a homogenous temperature distribution on the outside surface of the tube but a large temperature gradient along the thickness direction of the tube because of the heat exchange between the tube and the mandrel. YANG et al [25] conducted an isothermal deformation flow analysis for the backward spinning of a BT20 thin-walled tube using a 3D rigid-plastic finite element method (FEM). Their simulation indicated that there was a neutral interface in the spinning deformation region. Metal on one side of the interface flowed in the opposite direction of the roller feed, and metal on the other side flowed toward the feed direction of the roller. CHEN and XU [26] studied the microstructure evolution of TA15 titanium alloy during hot power spinning and the effects of wall reduction on microstructure. They found that the lip deformation is the main deformation mechanism accompanying with twinning to coordinate the deformation. The microstructure gradually transforms into fine fibrous microstructure and the aspect ratio of primary α grain increases with increasing wall reduction. XU et al [27] observed the microstructure evolution during the hot spinning and annealing process of TA15 titanium alloy tubes and examined the mechanical properties of the spun tubes. Their results showed that as the spinning pass increased, the fiber microstructure gradually became oriented along the axial direction and the circumferential microstructure was also obviously stretched along the direction. At the same time, the tensile strength increased, and elongation decreased not only in the axial direction but also in the circumferential direction, which means that the tubular workpiece of titanium alloy can be strengthened bi-directionally by the spinning. The ductility of the spun tubes of TA15 alloy can also be improved by annealing at temperatures no higher than the recrystallization temperature with a slight decrease in tensile strength. SHAN et al [28] analyzed the correlation of the microstructure and texture with the deformation history in the hot backward flow spinning process of a BT20 tube by FEA and experiment. The results showed an obvious through-thickness inhomogeneity in deformation, microstructure and texture, especially when a thick-walled billet was spun. The textures in the outer and inner layers evolved differently because of their different inhomogeneous deformation histories. The inhomogeneity of the as-spun microstructure of the tube can be strongly reduced by a multi-pass and large deformation spinning.

2.1.2 Alpha-beta titanium alloys

Alpha-beta titanium alloys have been widely used because of their preferred processability and superior combination properties. They include TC3, TC4, TC11, TC21 and TC17. TC4 is a representative alloy that has been investigated by many Chinese researchers.

CHEN et al [29] established a 3D rigid-plastic macro FE model coupled with the thermal-mechanical effect for the hot shear spinning of a TC4 cone workpiece. Using this model, they found that the over-thinning of the workpiece and the large unfittability of the workpiece with the mandrel mainly resulted from the inhomogeneous thermal elastic deformation of the mandrel. YANG et al [30] studied the residual stress distribution of a TC4 cone in the hot spinning process using the X-ray technique. They found that the surface residual stress increased with increasing the feed rate. When the temperature exceeded 750 °C, a significant reduction in yield strength occurred, resulting in uneven deformation along the cross-section of the cone, while the residual stress increased dramatically. A half-cone angle that is too large or too small caused the residual stress to increase rapidly. To reduce the residual stress, the spinning deformation temperature for TC4 alloy should be controlled at 600−700 °C, and the half-cone angle should be maintained in the range of 30°−45°, with a lower feed ratio. LI et al [31] studied a multi-pass hot shear spinning process of a thin TC4 workpiece with a curvilinear shape by assuming the process as an isothermal one using FEM. They found that the stress−strain states of different areas in the workpiece changed with the process. They only simulated a few limited passes in the whole multi-pass spinning process because of high costs and long time involved in simulating the whole spinning passes.

WAN and LI [32] simulated the power spinning for cylindrical parts of titanium alloy with different technological parameters by ANYSYS software and investigated the influence of attack angle, percentage reduction and feed rate on spinning force. The results indicated that the spinning force decreased with the increase of attack angel while the spinning force increased with the increase of percentage reduction and feed rate. LI et al [33] also simulated a hot conventional spinning process of transforming a TC4 cone into a TC4 tube with a large ratio of height to diameter, and reported the influence of key parameters on the process, including the roller tracks and spinning pass as well as the clearance between the mandrel and the roller. The results showed that the stress−strain states were also different in different areas during the process. Six passes were used in their study to avoid defects due to overlarge thickness reduction at one pass. TIAN et al [34] compared the spinning force and the fittability of a TC4 alloy tube with the mandrel between a hot forward spinning and a hot backward spinning by FEM. The results showed that the maximum spinning force during the hot backward spinning was larger than that during the hot forward spinning and the fittability was poorer during the former process.

2.1.3 Metastable beta titanium alloys

Metastable beta titanium alloys have a high specific strength and excellent corrosion resistance as well as desirable mechanical working properties and age strengthening properties. They include TB2, TB8, Ti-5523, Ti-451, and so forth.

ZHAO et al [35] investigated the microstructure, mechanical properties, deformation-strengthening effect and plastic deformation mechanism of TB2 tubes after hot flow spinning. The results showed that the qualified tubes can be spun for a spinning temperature of 700 °C, reduction per pass of 20%−30% and feed rate in the range of 0.5−1.0 mm/r. MAO et al [36] analyzed the flow spinning feasibility for a Ti-5523 titanium alloy on the basis of some hot compressive deformation experiments. The results showed that the proper spinning temperature for the alloy should be approximately 650−750 °C. The feed rate and rotating speed should be determined for each pass since this alloy is not a strain-rate-sensitive material. WANG et al [37] studied the hot flow spinning feasibility of a Ti-451 alloy and experimentally investigated the effects of spinning temperature, reduction per pass and feed rate on the quality of Ti-451 spinning products. The results showed that the Ti-451 alloy has good hot spinning deformation performance, with the total spinning working rate reaching 90%. The temperature of the first pass should be 800−850 °C, and the temperature of subsequent passes should be properly reduced while increasing in the cumulative working rate and thinning in the wall. The final pass should adopt a lower spinning temperature, a smaller reduction ratio and a slower feed rate, to avoid build-up and folding and to ensure high dimensional precision.

For titanium alloys, inhomogeneous deformation due to uneven temperature distribution were found and analyzed in hot spinning process by FEM. The microstructures were also found clearly orientated along the spinning direction investigated by experiments. Based on these researches, the suitable spinning temperature range for titanium alloys was considered to be 600−800 °C.

2.2 Magnesium alloys

As one type of lightweight alloys used widely, magnesium alloys are currently the lightest structural materials with low density, high specific strength, specific stiffness and superior damping capacity [38−40]. They are known as future-oriented, environmentally friendly, practical structural metals [41−43].

YANG et al [44] established a 3D elastic-plastic macro FE model coupled with the thermal-mechanical effect for the hot splitting spinning of forming an AZ31 alloy round blank into a “Y” workpiece with bilateral flanges. They investigated the field distributions of the deformed workpiece, and examined the influence of the initial temperature of the blank and the feed rate of the roller on the forming quality of the deformed flanges. YOSHIHARA et al [45] investigated the thickness distribution of an AZ31-O dome formed from a tube by hot conventional neck-spinning at 300 °C based on FEA. The feasibility of forming a magnesium alloy tube was demonstrated by their spinning experiments. Furthermore, the wall thickness of the dome can be controlled by the path of the roller even though the thickness of the formed dome region was desired as three times the initial thickness of the tube. FAN and LI [46] studied the forming feasibility of AZ31 magnesium alloy sheet which was heated by friction. The results indicated that the plastic deformability of magnesium alloy sheet is increased with the sheet metal temperature increasing from 200 °C to 450 °C with friction warming effects. The parameters such as the feed rate, roller path and lubrication condition have a significant influence on the forming of magnesium alloy sheet. MURATA et al [47] investigated the strain distribution, forming limit, mechanical properties, hardness and accuracy of AZ31 tubes spun by heated roller tools. They claimed that the forming limit was improved greatly when the spinning temperature was higher than the recrystallization temperature; the tensile strength was higher than the original strength due to work hardening, but the ultimate tensile strength decreased with the increment in the reduction when the spinning temperature was high. Using FEA and experiments, LI [48] analyzed the hot flow spinning deformation behavior of an AZ81 cast magnesium alloy tube and the effect of the spinning pass, thinning rate and spinning temperature on the microstructure. The results showed that the inhomogeneous deformation through-thickness of the AZ81 alloy tube during hot spinning is similar to that of titanium alloys revealed by LI et al [19] and SHAN et al [28]. An obvious grain refinement occurred in the process. However, the degree of grain refinement with deformation was limited. Furthermore, a low temperature was beneficial to the grain refinement while re-heating between passes resulted in grain growth. They found that for small deformation degree, fragmentation of polycrystalline deformation played an important role, and as deformation degree increased, dynamic recrystallization gradually dominated. In addition, there was a flow line in the microstructure of the AZ81 alloy tube after hot spinning.

The characteristics of magnesium alloys were similar with those of titanium alloys except the suitable temperature range of magnesium alloys was considered to be 200−450 °C. With this temperature range, refined grain will be got.

2.3 Aluminum alloys

Aluminum alloys have received much attention because of their light weight, good corrosion resistance, superior external appearance, heat-resistant stability, and high temperature mechanical and fatigue properties [49−51]. Although most of spinning processes for aluminum alloys are performed at room temperature, if a large reduction per pass and a high forming limit are required, the spinning for the alloys must be performed at elevated temperatures to shorten complex process chains [52−54].

AKKUS and KAWAAHARA [55] experimentally studied the thickness distribution of a 6061-O dome under hot conventional spinning and proposed a simple formulation for predicting the thickness distribution of the dome. To achieve sufficient thickness of the dome after the spinning operation, a two-step spinning process for the Al tube end closure was proposed to thicken the boss of the dome. Firstly, the boss was deformed to a diameter smaller than the desired. The boss was then modified to obtain a greater boss diameter. The experimental results indicated that the proposed process could provide a greater boss thickness than conventional spinning. YANG et al [56] experimentally studied the effects of heating temperature, feed rate and half-cone angle on the residual stress distribution of a 5A06 aluminum alloy workpiece after hot shear spinning. They claimed that a spinning deformation temperature in the range of 300−400 °C was helpful for reducing residual stress on the workpiece surface. MORI et al [57] developed a hot shear spinning process for a cast aluminum alloy (7.36%Si, 0.18%Fe, 0.05%Cu, 0.02%Mn, 0.57%Mg, 0.01%Zn, 0.06%Ti, mass fraction) to eliminate casting defects and to obtain a workpiece with desired wall thickness distribution. They indicated that dendrites and shrinkage cavities in cast aluminum alloys could be successfully eliminated through hot shear spinning, and the presence of surface cracks around the corner of the mandrel caused by large shear deformation was reduced by decreasing the feed rate of the roller and increasing the tip radius of the roller. They also indicated that hot shear spinning was effective in improving the mechanical properties of cast aluminum alloy workpieces. WANG [58] established a 3D elastic-plastic FEM model for the hot tube spinning of the cast aluminum 7075 and investigated the hot deformation behavior during spinning process. They found that heat gradient appeared in both the axial and thick direction due to the heat exchange and friction heat. Furthermore, the increase of preheat temperature would increase the inhomogenity of thickness, the lower feed rate and greater roller angel would increase homogemity of wall thickness.

RADOVIC and NIKACEVIC [59] studied the deformation behavior and microstructure of AlMg6Mn alloy during hot shearing spinning by means of mechanical characterization, optical and SEM-EDS microscopy. The results showed that the grain structure developed during shear spinning is refined gradually. The grains elongate in axial direction with the increase of reduction, and also stretch along circumferential direction. Optimal combination of strength and elongation was observed. This is attributed to grain refinement and dislocation reactions with particles and atoms of Mg and Mn in solid solution. XIAO et al [60] investigated the effect of hot backward flow spinning process on the microstructure and mechanical properties of spray-deposited and hot extruded pipes (SDHEPs) of an Al−8.5Fe−1.3V−1.7Si alloy. The results showed that the fiber microstructures of the SDHEPs were severely distorted, the broken oxide pieces were further cracked and redistributed, the previous weak binding particle boundaries decreased and disappeared, and the overall microstructures after spinning were characterized by a more uniform continuum. All of these microstructural changes helped to improve the mechanical properties of the Al−8.5Fe−1.3V−1.7Si alloy SDHEPs and to weaken the anisotropy of the materials. MAO and SHEN [61] analyzed the microstructure and mechanical properties of an as-forged 6061 alloy tube after hot flow spinning. The results showed that the microstructure was fine and homogeneous and the plasticity and fracture toughness of the tube were improved after spinning. LÜ et al [62] reported an experimental investigation on the hot conventional spinning process of a conical 5A06 aluminum alloy tube. In the process, a thick-walled tube was formed as a thin-walled conical tube with a half-cone angle of less than 1° by controlling the spinning temperature, roller feed rate, and so forth. The results showed that the temperature was the most important parameter.

In addition, HOMBERG et al [63] investigated the manufacturing of complex functional graded AlMgSi0.5 and Al99.5 workpieces by using friction-spinning experiments. A strong grain refinement in the deformed workpieces was observed. By using the friction-spinning process, large deformation degree can be realized and more complex geometries can be produced, workpiece properties can be also specifically set.

For aluminum alloys, hot spinning would get higher forming limits and finer grain compared with spinning at room temperature. Casting defects could also be eliminated, so the plasticity and fracture toughness of the tube were improved after spinning.

2.4 Metal composites

Metal composites or clad metals, consisting of two or more metals, have been increasingly used in many industries because of their unique properties, which a single material does not have. Their unique properties involve enhanced mechanical properties, corrosion resistance, electrical conductivity, fatigue characteristics and wear resistance, which can meet the main industrial demands [64−66]. As one of the new manufacturing and processing methods for metal composites, spin-extrusion was proposed a few years ago.

NEUGEBAUGER et al [67] presented the macro FEA and experimental results of the contact and forming conditions of AZ31/AlMgSi1 double-layered tubes with respect to a spin-extrusion process. The results showed that it was feasible to form magnesium/aluminum double-layered tubes by spin-extrusion process. The temperature and layer thickness in the process had a strong effect on the bonding strength. Their FE simulations for double-layered spin-extrusion process can provide insight in the complex thermo-mechanics of the process, but they cannot provide distinct information about the bonding process.

MOHEBBI and AKBARZADEH [68] successfully applied flow spinning to produce two-layered thin-walled composite tubes consisting of the same AA 1050 aluminum. Then, they [69,70] extended the process to two-layered composite tubes consisting of copper and AA 1050 aluminum. The bonding quality of the composite tubes under various thickness reductions and process temperatures was evaluated. The results showed that the thickness reduction and process temperature have a strong impact on the bonding strength. Severe shear strains occurring during the spin-bonding process made it appropriate for bonding copper to aluminum.

Hot spinning provided a new method to produce metal composites parts. Researches on hot spinning for metal composites were mainly studied by FEM and the underlying bonding mechanism needs to be further investigated.

2.5 Research problems of hot spinning on lightweight workpiece materials

Most of workpieces of lightweight metals in hot spinning are simple in shape, such as cones and tubes. Thus, the potential of hot spinning for forming complex components has not been achieved due to low dimensional precision and poor fittability to the mandrel resulting from process complexity and difficulty in controlling temperature and its distribution and gradient. Therefore, hot spinning for complex components of light metals that are difficult to form is required to obtain products with high quality and performance but light weight.

Although there are a lot of FEAs on hot spinning, these FEAs only focus on the macro deformation analysis for hot spinning, and FEAs on the microstructure, especially for grain refinement, are rare for hot spinning. Furthermore, strong grain refinements in as-spun parts during hot spinning processes have been observed [63] and microstructure always varies with the process. Therefore, more researches on the microstructure or combination of macro and micro deformation of as-spun parts during hot spinning using FEM, especially for grain refinement, should be conducted.

Current FEAs have limited prediction precision in hot spinning since they neglected the effects of springback and cooling after hot spinning, which have an important role in the prediction precision in dimension and shape of as-spun parts. Thus, effects of springback and cooling process need to be considered in the FEAs for hot spinning to improve the prediction precision. Furthermore, the simulation efficiency for hot spinning is low due to spinning characteristics of continuous and local loading deformation and complicated heat effects among workpiece, mandrel and roller. This low efficiency and limited precision confine the application of FEM to the hot spinning of complex workpieces. Thus, more attention should be given to improve the efficiency and precision of FEAs for hot spinning of complex workpieces.

Considering the increasing requirements for metal composites in many industries because of their unique properties, the thorough investigations for hot spinning of metal composites should be conducted, especially in the research on the constitutive model and the bonding mechanism of composite metals.

3 Heating methods in hot spinning

In industrial spinning applications or experiments, eight heating strategies are currently employed, including flame heating, heating in a furnace, induction heating, heating by hot air in a chamber, laser heating, synchronous heating in a furnace with moving rollers, heating by a heated roller, and friction heating.

As a matter of convenience, the workpiece is often heated continuously with spinning process using flame of acetylene oxygen, coal gas, liquid oil or fuel oil, as shown in Fig. 2 [45]. XU et al [27], YANG et al [30], WANG et al [37], AGHION et al [42], YOSHIHARA et al [45], AKKUS and KAWAHARA [55], MORI et al [57] and HAMED and ALIREZA [71] used acetylene gas burners or acetylene oxygen torches to heat workpieces. Although flame heating is widely used, it is evident that it has the following significant disadvantages: 1) the temperature and its distribution of the workpiece cannot be accurately controlled with a temperature difference up to 300 °C in the process [22]; 2) it is difficult to achieve qualified workpieces because of the inhomogeneous temperature distribution with a temperature difference in thickness direction up to 80 °C though the thickness is only 4 mm [72].

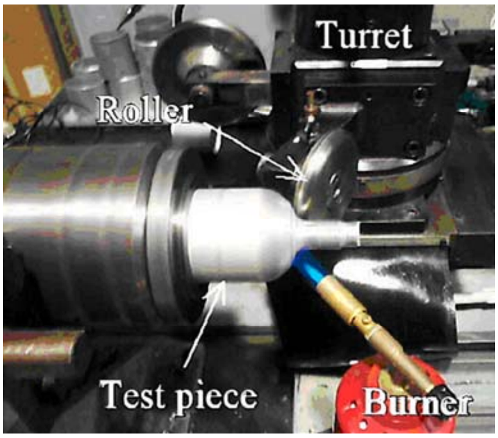

Fig. 2 Schematic picture of flame heating spinning [45]

Another portable heating method consists of heating before spinning in a furnace or using high frequency or medium frequency induction heater. HUANG et al [73] heated a tube to forming temperature using a high frequency induction heater before spinning. There is no doubt that furnace heating or induction heating can provide homogeneous temperatures for the workpiece before spinning, but upon spinning, the temperature of the workpiece will decrease sharply since there is no heat to supply during spinning that would affect the quality of the spun workpiece.

It is clear that a heating strategy is needed to allow for simultaneous heating of the forming zone during spinning. Heating the workpiece locally with a laser, heated rollers or a synchronous heating furnace constitutes a very promising approach for fulfilling this need. Figure 3 shows the principle of laser-heating spinning [74]. Using the method, KLOCKE and WEHRMEISTER [74] developed the hybrid process of laser-assisted metal spinning. They reported that when the metal spinning technique was combined with heat applied by a laser beam, even materials such as titanium and nickel-based alloys as well as strain-hardened stainless steel alloys can be formed without any intermediate annealing steps. MURATA et al [47] invented a new computer numerical control (CNC) spinning machine, which has roller tools with heaters. The heated roller tools can heat magnesium tubes and form them into various shapes by spinning. However, there are still some disadvantages to the local heating method: 1) a high thermal gradient is caused by localized heating, which may potentially result in the generation of high residual stress and affect the product geometry during and after spinning [10], and 2) the workpiece temperature is difficult to control because of local heating and complicated thermal transients [10]. Synchronous heating in a furnace with moving rollers is another possible local heating method. XIAO et al [60] used an electrical resistance furnace synchronously moving with rollers to heat a tube workpiece to 450 °C, as shown in Fig. 4. Compared with the former two local heating methods, this method can achieve a more homogenous temperature distribution while this method needs more complicated structure.

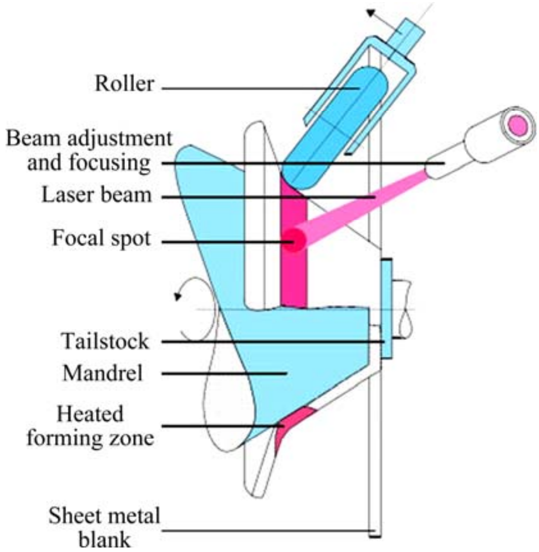

Fig. 3 Schematic diagram of laser-heating spinning [74]

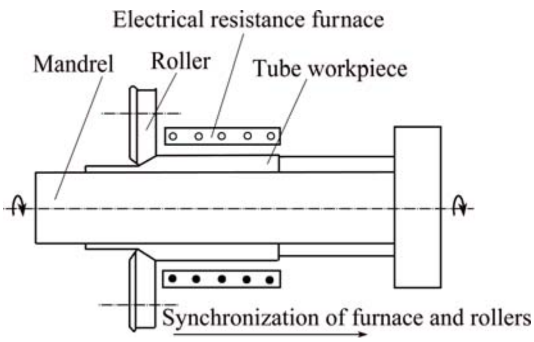

Fig. 4 Schematic diagram of backward spinning process with electrical resistance furnace synchronously moving with rollers [60]

To avoid the disadvantages of the above-mentioned heating methods, MORI et al [57] enclosed a spinning setup in a chamber and used hot air to heat cast aluminum blanks, as shown in Fig. 5. However, all devices in the spinning setup must have high temperature strength, and special lubricate measures are required. The materials required in the device could bear high spinning temperature, such as titanium alloy. These requirements for the material of devices and lubrication make a big difference to spinning quality and these requirements will lead to an increase in the cost of the manufactured products.

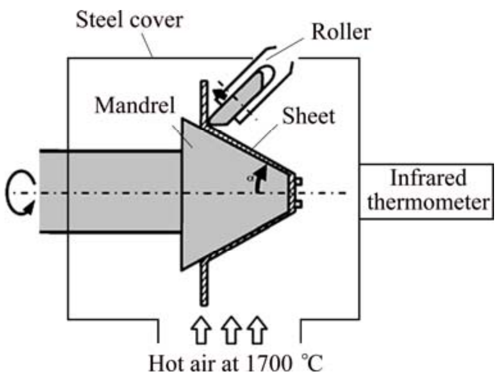

Fig. 5 Schematic diagram of spinning with hot air [57]

In addition, HOMBERG et al [63] used frictional heat between workpiece and friction tool/roller (as shown in Fig. 6) to increase workpiece temperature. The combination of frictional heat with spinning process makes it possible to realize larger deformation to produce the workpiece with more complex geometry. Therefore, the usage of frictional heat may be a potential heating method which can be applied widely to hot spinning process. However, how to control frictional heat is a complicated work for different combinations of workpiece and friction tool/roller with various materials and shapes. And severe friction between workpiece and friction tool/roller will lead to the decrease in the surface quality of the workpiece.

Summing up the above researches on heating methods, there are the following problems.

1) Heating methods during the spinning process will result in large thermal gradient. The heating methods only before the spinning process will cause a large temperature decrease with the spinning process going on.

2) Some heating methods, such as heating with hot air, not only require that all devices in the spinning setup must have high temperature strength, but also require special lubricate measures for the setup, especially for workpiece materials with high spinning temperature.

3) The usage of frictional heat may be a potential heating method which can be applied widely to hot spinning process. However, the complexity of how to control frictional heat and the decrease in the surface quality of the workpiece resulting from severe friction limited the usage of this heating method in spinning.

Therefore, it is necessary to develop new heating methods or to modify the old heating methods to make the heating process easily achevied at low cost, and to guarantee a controllable temperature with small gradient.

4 Temperature boundary condition in FEA for hot spinning

The temperature boundary condition in FEA for hot

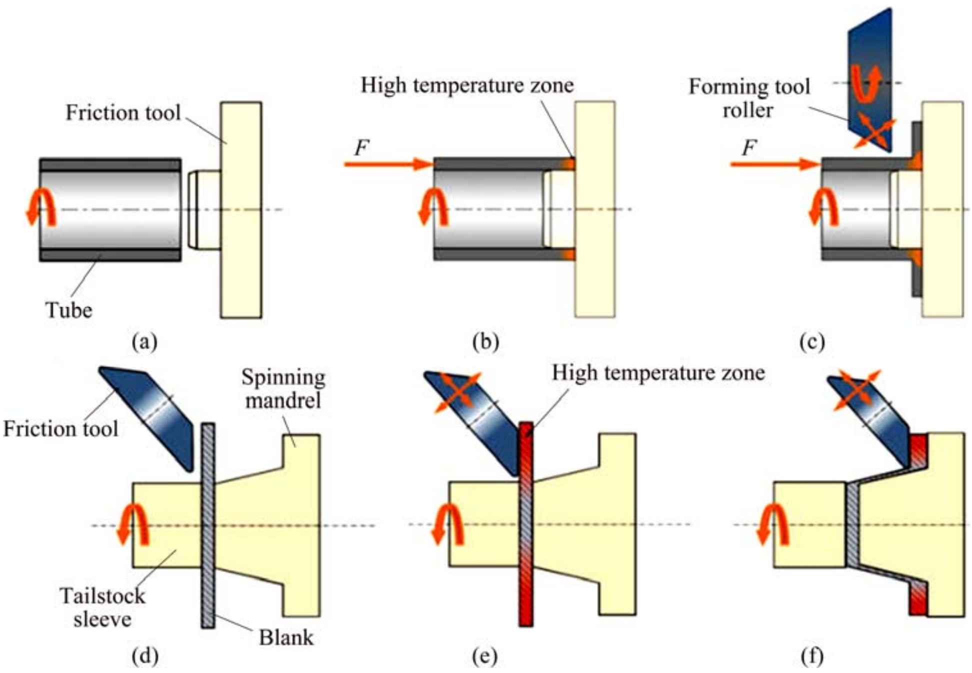

Fig. 6 Process principle of friction spinning for tubular components and parts made of sheet metal [63]: (a) Set tube on friction tool; (b) Heat generation by friction tube end; (c) Friction spinning for tubular parts; (d) Set sheet metal on friction tool; (e) Heat generation by friction sheet surface; (f) Friction spinning for sheet metal components

spinning involves treatments for external heating and heat effects. In sum, there are three methods related to simplifications for external heating and heat effects.

In the first method, the action of the external heating is simplified by assigning an initial temperature to the workpiece, and all heat effects are neglected. This temperature boundary condition can be defined as

$$T(x, y, z, t)= T(x, y, z, t_0) \tag{1}$$

where $T(x, y, z, t_0)$ is the temperature distribution at the time t=0, and $T(x, y, z, t)$ is the temperature distribution during deformation. Thus, the hot spinning process based on this method is assumed to be isothermal, as in the simulations by YANG et al [25], LI et al [31], LI et al [33], TIAN et al [34], KAWAI et al [43], YOSHIHARA et al [45], and HUANG et al [73]. The results obtained using this method may not agree well with experiments because of the ignoring of temperature variation resulting from heat generation and heat exchange during actual spinning processes.

A great deal of heat would generate resulting from dramatic deformation of metals during spinning. Even for the cold spinning process, these heat effects should sometimes be considered since they have important role in the dimensional precision and temperature value and distribution [75,76]. For hot spinning process, these effects become more prominent and cannot be ignored. So, in the second and third methods for the treatment of temperature boundary condition, some kinds of heat effects were considered.

In the second method, though the action of the external heating is simplified by assigning an initial temperature to the workpiece, some kinds of heat effects are still considered, as in the simulation for the splitting spinning of an AZ31 alloy by YANG et al [44]. This temperature boundary condition can be defined as

$$\begin{cases} q_\mathrm{d} = h_\mathrm{d}(T - T_\mathrm{d}) \\ q_\mathrm{c} = h_\mathrm{c}(T - T_\mathrm{f}) \\ q_\mathrm{r} = \varsigma\varphi(T^4 - T_\mathrm{c}^4) \end{cases} \tag{2}$$

where q_d is the contact surface heat flux density; h_d is the contact thermal conductivity; T_d is the mould temperature; T is the blank temperature; q_c is the convective heat flux density; h_c is the convection coefficient; T_f is the fluid temperature; q_r is the radiation flux density; ς is the emissivity of material; φ is the Stefan−Boltzmann constant; T_c is the ambient temperature. They set the initial temperature of the AZ31 blank as 300 °C and the heat exchange between the blank and the external environment by convection and radiation and the contact heat conducted from the blank to the die are concerned. Meanwhile, the plastic deformation energy of the blank was mostly converted into heat energy and internal energy.

With the last method, the external heating is usually translated into an internal heat source through the heat current density while the main heat effects are also considered. In the simulation for the hot shear spinning process, this simplification for the external heating was used by LI et al [19]. This temperature boundary condition can be defined as

$$\begin{cases} q_\mathrm{d} = h_\mathrm{d}(T - T_\mathrm{d}) \\ q_\mathrm{c} = h_\mathrm{c}(T - T_\mathrm{f}) \\ q_\mathrm{r} = \varsigma\varphi(T^4 - T_\mathrm{c}^4) \\ Q = \rho c\Delta T = \rho c(T_\mathrm{r} - T_0) \end{cases} \tag{3}$$

where Q is the total heat; ρ is the blank density; c is the blank specific heat capacity; T_r is the heating temperature of blank; T_0 is the initial temperature of blank. They divided the blank into several annuluses (Fig. 7) in response to the bore of the gas burner and the feed speed of the roller. They applied a body heat flux to each annulus following the movement of the roller. A mandrel that was preheated to a temperature level before spinning was used to prevent a sharp workpiece temperature decrease. CHEN and KANG [24] and CHEN et al [29] simulated the action of the external heating during the hot shear spinning process and hot flow spinning process by starting with a known flame temperature and heat convection coefficient between the environment and the workpiece. To simulate the actual situation, the heat exchange between the mandrel and the connector of the spinning machine was taken into consideration in their simulation.

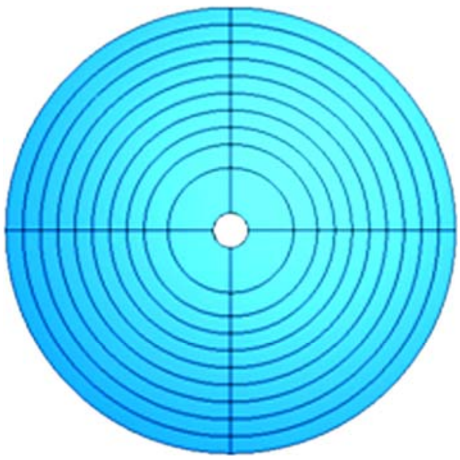

Fig. 7 Distribution of annuluses in blank [19]

In most of FEAs for hot spinning, the simplifications for thermal boundary conditions make them differ a lot from actual spinning thermal conditions or environment, leading to differences in the temperature distribution and other indexes in comparison to actual hot spinning. Therefore, more detailed treatments for thermal boundary conditions in FEA for hot spinning need to be developed.

5 Summary and future development of hot spinning

In this paper, researches on the hot spinning process were reviewed with regard to lightweight workpiece materials, practical heating methods and simplifications for thermal boundary conditions in FEA for hot spinning. Although hot spinning can be a very complicated process because of complex deformation characteristics and the difficulty in controlling temperature and its distribution and gradient in workpiece, it still has great development potential for the production of complex parts of difficult-to-form light metals with high performance and light weight.

Some issues and future prospects for hot spinning technique can be summarized as follows.

1) Characterization of the macro-micro mechanism of hot spinning of difficult-to-deform lightweight metals. Due to the lack of analysis, prediction and optimal control of unequal deformation in hot spinning of difficult-to-deform lightweight metals, multi-scale modeling has become a primary scientific challenge for the whole process of hot spinning of difficult-to-deform lightweight metals.

2) Improvement in efficiency and precision of FEA for hot spinning of difficult-to-deform lightweight metals. The efficiency and precision are low in the FEA for hot spinning due to the ignorance of springback and cooling after hot spinning, continuous characteristic of spinning and local loading deformation and complicated heat effects among workpiece, mandral and roller. The low efficiency and precision confine the application of FEAs to the hot spinning of complex workpieces of difficult-to-deform lightweight metals. Thus, more attention should be given to improve the efficiency and precision of FEAs for hot spinning of complex workpieces of difficult-to-deform lightweight metals.

3) Systematic and thorough investigations on hot spinning for metal composites. Considering the increasing requirements for metal composites in many industries because of their unique properties, systematic and thorough investigations for hot spinning of metal composites should be conducted, especially in the research on the constitutive model and the bonding mechanism of composite metals.

4) Heating methods for practical spinning to obtain a more homogeneous temperature distribution with small gradient. There are disadvantages or difficulties of existed heating method in temperature variation and control, special requirement for the material of devices and lubrication measures for the setup. Therefore, it is necessary to develop new heating methods or to modify the old heating methods to make the heating process easily achieved at low cost, and to guarantee a controllable temperature with small gradient.

5) Full consideration of thermal effects and appropriate treatment methods for heating boundary conditions in FEA for hot spinning of difficult-to-deform lightweight metals. The ignorance of thermal effects and simplifications for thermal boundary conditions in most of FEAs for hot spinning make the conditions differ a lot from actual spinning thermal conditions or environment, leading to differences in the temperature distribution and other indexes in comparison to actual hot spinning. Therefore, full consideration of thermal effects and more detailed treatment for thermal boundary conditions in FEAs need to be developed for hot spinning of difficult-to-deform lightweight metals.

References

[1] BARINYIMA N, PERICLES P, THEOKLIS N. Performance assessment of simple and modified cycle turboshaft gas turbines [J]. Propulsion and Power Research, 2013, 2(2): 96−106.

[2] ALEXANDER P, YURIY S, ELENA L. Research of material for uncooled nozzle extensions of liquid rocket engines [J]. Acta Astronautica, 2009, 64: 22−27.

[3] ZHAO Zhong, GAO Yong-wei. Experimental study of flow-induced tones of nose cones in high-speed flows [J]. Technical Acoustics, 2007, 26(1): 96−100. (in Chinese)

[4] ZHAO Lin-yu, HAN Dong, ZHANG Li-wu, LI Zeng-hui, WANAG Bei-ping, YANG Yan-tao, GONG Jun-shan. Typical application and development of metal spinning technology and equipment [J]. Forging & Stamping Technology, 2007, 32(6): 18−26. (in Chinese)

[5] GRASS H, KREMPASZKY C, WERNER E. 3-D FEM-simulation of hot forming processes for the production of a connecting rod [J]. Computational Materials Science, 2006, 36: 480−489.

[6] KALPAKJIAN S, RAJAGOPAL S. Spinning of tubes: A review [J]. J Applied Met Working, 1982, 2(3): 211−223.

[7] XU Y, ZHANG S H, LI P, YANG K, SHAN D B, LU Y. 3D rigid–plastic FEM numerical simulation on tube spinning [J]. Journal of Materials Processing Technology, 2001, 113(1−3): 710−713.

[8] CHATTI S, HERMES M, WEINRICH A, BEN-KHALIFA N. New incremental methods for springback compensation by stress superposition [J]. Prod Eng Res Devel, 2009, 3: 137−144.

[9] XIA Q X, XIAO G F, LONG H, CHENG X Q, SHENG X F. A review of process advancement of novel metal spinning [J]. International Journal of Machine Tools and Manufacture, 2014, 85: 1419−1435.

[10] MUSIC O, ALLWOODA J M, KAWAI K. A review of the mechanics of metal spinning [J]. Journal of Materials Processing Technology, 2010, 210: 3−23.

[11] WONG C C, DEAN T A, LIN J. A review of spinning, shear forming and flow forming process [J]. International Journal of Machine Tools and Manufacture, 2003, 43: 1419−1435.

[12] NEUGEBAUER R, ALTAN T, GEIGER M, KLEINER M. Sheet metal forming at elevated temperatures [J]. Annals of the CIRP, 2006, 55(2): 793−816.

[13] JESWIET J, GEIGER M, ENGEL U, KLEINER M, SCHIKORRA M, DUFLOU J, NEUGEBAUER R, BARIANI P, BRUSCHI S. Metal forming progress since 2000 [J]. CIRP Journal of

Manufacturing Science and Technology, 2008, 1(1): 2−17.

[14] YANG H, FAN X G, SUN Z C, GUO L G, ZHAN M. Recent developments in plastic forming technology of titanium alloys [J]. Science China Technological Science, 2011, 54(2): 490−501.

[15] WANG Peng-cheng, KAWAI Kenichi, YUE Zhi-yong. Spinning technology of magnesium alloy in Japan [J]. Forging & Stamping Technology. Technol, 2008, 33(6): 6−12. (in Chinese)

[16] BOYER R R. An overview on the use of titanium in the aerospace industry [J]. Materials Science and Engineering A, 1996, 213: 103−114.

[17] GORYNIN I V. Titanium alloys for marine application [J]. Materials Science and Engineering A, 1999, 263(2): 112−116.

[18] GURAPPA I. Protection of titanium alloy components against high temperature corrosion [J]. Materials Science and Engineering A, 2003, 356(1−2): 372−380.

[19] LI Hu, ZHAN Mei, YANG He, CHEN Gang, HUANG Liang. Coupled thermal-mechanical FEM analysis of power spinning of titanium alloy thin-walled shell [J]. Chinese Journal of Mechanical Engineering, 2008, 44(6): 187−193. (in Chinese)

[20] ZHAN M, WU T C, JIANG Z Q. Influence of process parameters on hot power spinning of titanium alloy thin-walled shell [C]//Proceedings of the International Conference on Advances in Materials & Processing Technologies, Manama, Kingdom of Bahrain, 2008: 155.

[21] ZHAN M, LI T, YANG H, WANG Q L, LI H. Effects of heating temperatures on hot spinning of TA15 alloy thin-walled shell [C]//Proceedings of the 12th Word Conference on Titanium. Beijing, China, 2011: 120.

[22] ZHAN Mei, WANG Qiao-ling, HAN Dong, YANG He. Geometric precision and microstructure evolution of TA15 alloy by hot shear spinning [J]. Transactions of Nonferrous Metals Society of China, 2013, 23(6): 1617−1627.

[23] HUANG L, ZENG R, ZHANG X T, LI J J. Study on plastic deformation behavior of hot splitting spinning of TA15 titanium alloy [J]. Materials & Design, 2014, 58: 465−474.

[24] CHEN Yu, KANG Da-chang, JIN Xiao-ou. FEM coupled thermal simulation of warm power spinning of cylindrical workpiece of titanium alloy [J]. Journal of Harbin Institute Of Technology, 2006, 38(1): 191−193. (in Chinese)

[25] YANG Guo-ping, XU Wen-chen, CHEN Yu, SHAN De-bin, KANG Da-cheng, LÜ Yan. Research on material flow rule of backward tube spinning process [J]. Journal of Plastic Engineering, 2008, 15(6): 48−52. (in Chinese)

[26] CHEN Yong, XU Wen-chen, SHAN De-bin, GUO Bin. Microstructure evolution of TA15 titanium alloy during hot power spinning [J]. Transactions of Nonferrous Metals Society of China, 2011, 21(S2): s323−s327.

[27] XU Wen-chen, SHAN De-bin, WANG Zhen-long, YANG Guo-ping, LÜ Yan, KANG Da-chang. Effect of spinning deformation on microstructure evolution and mechanical property of TA15 titanium alloy [J]. Transactions of Nonferrous Metals Society of China, 2007, 17(6): 1205−1211.

[28] SHAN D B, YANG G P, XU W C. Deformation history and the resultant microstructure and texture in backward tube spinning of Ti−6Al−2Zr−1Mo−1V [J]. Journal of Materials Processing Technology, 2009, 209: 5713−5719.

[29] CHEN Yu, KANG Da-chang, JIN Xiao-ou. FEM coupled thermal simulation of warm shear spinning of cone workpiece of titanium alloy [J]. Materials Science and Technology, 2006, 14(1): 18−21. (in Chinese)

[30] YANG Zhi, HOU Hong-liang, ZHOU Wen-long. Study on distribution of residual stress to titanium alloy by shear spinning [J]. China Metal Forming Equipment & Manufacturing Technology, 2008(5): 99−101. (in Chinese)

[31] LI Qi-jun, LÜ Hong-jun, WANG Qi. FEM numerical simulation of spinning processing for thin TC4 alloy workpiece with curvilinear shape [J]. Journal of Tianjin Polytechnical University, 2008, 27(2): 61−65. (in Chinese)

[32] WAN Qiong, LI Fu-guo, LI Chao-ling, LI Yan-feng. Simulation on power spinning process for cylindrical parts of titanium alloy [J]. Hot Working Technology, 2012, 41(1): 98−100. (in Chinese)

[33] LI Qi-jun, LÜ Hong-jun, WANG Qi. FEM numerical simulation of spinning processing for workpiece of TC4 alloy with great ratio of height to diameter [J]. Aerospace Materials & Technology, 2006(S1): s88−s92. (in Chinese)

[34] TIAN Hui, HUANG Hai-qing, CHEN Guo-qing, ZHOU Wen-long. Effects of power spinning processing parameters on cylinders of TC4 alloy [J]. Aerospace Manufacturing Technology, 2009(5): 14−17. (in Chinese)

[35] ZHAO Yun-hao, WANG Fa-chun, SHEN Jian. Investigation on microstructure and mechanical properties of TB2 titanium alloy after tube-spinning deformation [J]. Forging & Stamping Technology, 2007, 32(6): 87−90. (in Chinese)

[36] MAO Bai-ping, WANG Fa-chun, ZHAO Yun-hao, SHEN Jian. Study on spinning properties of titanium alloy [J]. Chinese Journal of Rare Metals, 2004, 28(1): 271−273. (in Chinese)

[37] WANG Jian-guo, YANG Ying-li, SU Hang-biao, ZHAO Bin, ZHAO Heng-zhang. Study on power spinning feasibility of high strength & toughness Ti-451 alloy [J]. Titanium Ind Prog, 2009, 26(3): 30−33. (in Chinese)

[38] MORDIKE B L, EBERT T. Magnesium: Properties— applications–potential [J]. Materials Science and Engineering A, 2001, 302: 37−45.

[39] ATAYA S, EI-MAGD E. Modeling the creep behavior of Mg alloys with and without short-fiber reinforcement [J]. Computational Materials Science, 2007, 39(1): 155−159.

[40] CHANGIZIAN P, ZAREI-HANZAKI A, ROOSTAEI A A. The high temperature flow behavior modeling of AZ81 magnesium alloy considering strain effects [J]. Materials & Design, 2012, 39: 384−389.

[41] LIN Y C, CHEN X M, LIU Z H, CHEN J. Investigation of uniaxial low-cycle fatigue failure behavior of hot-rolled AZ91 magnesium alloy [J]. Int Journal of Fatigue, 2013, 48: 122−132.

[42] AGHION E, BRONFIN B, ELIEZER D. The role of the magnesium industry in protecting the environment [J]. Journal of Materials Processing Technology, 2001, 117(3): 381−385.

[43] KAWAI K, KOYAMA H, KAMEI T, KIM W. Boss forming, an environment-friendly rotary forming [J]. Key Eng Mater, 2007, 344: 947−953.

[44] YANG H, HUANG L, ZHAN M. Coupled thermo-mechanical FE simulation of the hot splitting spinning process of magnesium alloy AZ31 [J]. Computational Materials Science, 2010, 47(3): 857−866.

[45] YOSHIHARA S, McDONALD B, HASEGAWA T, KAWAHARA M, YAMAMOTO H. Design improvement of spin forming of magnesium alloy tubes using finite element [J]. Journal of Materials Processing Technology, 2004, 153−154: 816−820.

[46] FAN You-fa, LI Dong-nan, CHEN Wen-zhe. Study on spinning process of AZ31B magnesium alloy sheet [J]. Chinese Mechnical Engineering, 2012, 23(11): 1272−1275. (in Chinese)

[47] MURATA M, KUBOKI T, MURAI T. Compression spinning of circular magnesium tube using heated roller tool [J]. Journal of Materials Processing Technology, 2005, 162−162: 540−545.

[48] LI Bing. Research on hot spinning process and microstructure evolution of AZ81 [D]. Chongqing: Chongqing University, 2010. (in Chinese)

[49] KHAN A, LIU H W. Variable strain rate sensitivity in an aluminum alloy: Response and constitutive modeling [J]. International Journal of Plasticity, 2012, 36: 1−14.

[50] BASHFORD D. A review of advanced metallic and ceramic materials suitable for high temperature use in space structures [J].

Astronautica, 1990, 22: 137−144.

[51] CHOI S H, SUNG S Y, CHOI H J, SHON Y H, HAN B S, LEE K A. High temperature tensile deformation behavior of new heat resistant aluminum alloy [J]. Procedia Engineering, 2011, 10: 159−164.

[52] CHANG S C, WANG C C, HUANG C A, CHANG Y, CHENG T L. Fabrication of 2024 aluminum spun tube using a thermomechanical treatment process [J]. Journal of Materials Processing Technology, 2001, 108: 294−299.

[53] RAMANA K V, SINGH M, GUPTA A, DEY R, KAPOOR A, RAO P V M. A manufacturability advisor for spun and roll formed sheet metal components [J]. International Journal of Advanced Manufacture Technology, 2006, 28: 249−254.

[54] FAZELI A R, GHOREISHI M. Investigation of effective parameters on surface roughness in thermomechanical tube spinning process [J]. International Journal of Advanced Manufacture Technology, 2009, 2: 261−270.

[55] AKKUS N, KAWAHARA M. An experimental and analytical study on dome forming of seamless Al tube by spinning process [J]. Journal of Materials Processing Technology, 2006, 173: 145−150.

[56] YANG Zhi, HOU Hong-liang, ZHOU Wen-long. Distribution rule of residual stress in aluminum alloy after shear spinning [J]. Avigation Manuf Technol, 2009(6): 78−80. (in Chinese)

[57] MORI K I, ISHIGURO M, ISOMURA Y. Hot shear spinning of cast aluminum alloy parts [J]. Journal of Materials Processing Technology, 2009, 209(7): 3621−3627.

[58] WANG En-le. Research on thermoplastic deformation behavior during power spinning for cast aluminum [D]. Nanchang: Nanchang Hangkong University, 2013. (in Chinese)

[59] RADOVIC L M, NIKACEVIC M, JORDOVIC B. Deformation behavior and microstructure evolution of AlMg6Mn alloy during shear spinning [J]. Transactions of Nonferrous Metals Society of China, 2012, 22(5): 991−1000.

[60] XIAO Yu-de, WU Yong-yu, LI Wen-xian, MA Zheng-qing, WANG Ri-chu. Effects of shear spinning process on microstructures and mechanical properties of extruded pipes of spray deposited Al−8.5Fe−1.3V−1.7Si alloy [J]. J Center South University (Science and Technology), 2005, 36(3): 358−363. (in Chinese)

[61] MAO Bai-ping, SHEN Jian. Effects of spinning deformation on microstructure and properties of 6061 Al-alloy tube [J]. Hot Working Technology, 2008, 37(11): 49−51. (in Chinese)

[62] LÜ Xin-yu, WANG Ben-xian, ZHANG Shi-hong, WU Yi, LI Ji-zhen, CHEN Fu-long, WANG Jian-fei. Experimental investigation on spin forming of conical LF6 aluminum alloy tubes with a small angle [J]. Forging & Stamping Technology, 2005(3): 43−46. (in Chinese)

[63] HOMBERG W, HORNJAK D, BEERWALD C. Manufacturing of complex functional graded workpieces with the friction-spinning process [J]. International Journal of Material Forming, 2010, 3(1): 943−946.

[64] PENG X K, HENESS G, YEUNG W Y. Effect of rolling temperature on interface and bond strength development of roll bonded copper/aluminum metal laminates [J]. Journal of Materials Science, 1999, 34: 277−281.

[65] ABBASI M, TAHERI A K, SALEHI M T. Growth rate of intermetallic compounds in Al/Cu bimetal produced by cold roll welding process [J]. Journal of Alloys and Compd, 2001, 319(1−2): 233−241.

[66] ZHAN Z L, HE Y D, WANG D R, GAO W. Cladding inner surface of steel tubes with Al foils by ball attrition and heat treatment [J]. Surf Coat Technol, 2006, 201(6): 2684−2689.

[67] NEUGEBAUGER R, MEINEL S, GLAß R, POPP M. Characterization of contact tensions during incremental forming of metal composites [J]. International Journal of Material Forming, 2010, 3(1): 667−670.

[68] MOHEBBI M S, AKBARZADEH A. A novel spin-bonding process for manufacturing multilayered clad tubes [J]. Journal of Materials Processing Technology, 2010, 210: 510−517.

[69] MOHEBBI M S, AKBARZADEH A. Accumulative spin-bonding (ASB) as a novel SPD process for fabrication of nanostructured tubes [J]. Materials Science and Engineering A, 2010, 528: 180−188.

[70] MOHEBBI M S, AKBARZADEH A. Fabrication of copper/ aluminum composite tubes by spin-bonding process: Experiments and modeling [J]. International Journal of Advanced Manufacture Technology, 2011, 54: 1043−1055.

[71] ZOGHI A, AREZOODAR A F, SAYEAFTABI M. Enhanced finite element analysis of material deformation and strain distribution in spinning of 42CrMo steel tubes at elevated temperature [J]. Materials & Design, 2013, 47: 234−242.

[72] HAN Dong, ZHAN Mei, YANG He. Deformation mechanism of TA15 shells in hot shearing spinning under various load conditions [J]. Rare Metal Materials and Engineering, 2013, 42(2): 243−248.

[73] HUANG C C, HUNG J C, HUANG C H, LIN C R. Finite element analysis on neck-spinning process of tube at elevated temperature [J]. International Journal of Advanced Manufacture Technology, 2011, 56(9−12): 1039−1048.

[74] KLOCKE F, WEHRMEISTER T. Laser-assisted metal spinning of advanced materials [C]//Proceedings of the Second International WLT-Conference on Lasers in Manufacturing 2003, München: AT-Verlag, 2003: 195−200.

[75] MARGHMALEKI I S, BENI Y T, NOGHREHABADI A R, KAZEMI A S, ABADYAN M. Finite element simulation of thermomechanical spinning process [J]. Procedia Engineering, 2011, 10: 3769−3774.

[76] LI Y, XIAO H, LIAN B, TANG Y, ZENG Z X. Forming method of axial micro grooves inside copper heat pipe [J]. Transactions of Nonferrous Metals Society of China, 2008, 18(5): 1229−1233.

难变形轻金属材料热旋成形综述

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摘 要：热旋成形因为可以用来制造复杂构件，提升材料的成形极限，降低成形力，减少加工工序而备受关注。本文综述室温下难变形的轻金属材料热旋成形的一些研究成果。这些金属包括钛合金，镁合金，铝合金等轻合金和金属复合材料。然后，讨论热旋成形中的加热方法以及对热旋成形有限元分析中温度边界条件的处理方法。最后，归纳总结难变形轻金属热旋成形的未来发展方向。

关键词：热旋；轻金属；加热方式；热边界条件；未来发展方向

(Edited by Yun-bin HE)