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ORIGINAL ARTICLE

Experimental analysis of electro-assisted warm spin forming of commercial pure titanium components

Kai Jin[1] · Jianhua Wang[1] · Xunzhong Guo[2] · Joseph Domblesky[3] · Hui Wang[1] · Xia Jin[1] · Runze Ding[1]

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Abstract
Aircraft manufacturers continue to use larger quantities of titanium components to increase strength and reduce weight. While various forming processes can be used, spin forming is particularly well suited for economically producing small and large quantities of axisymmetric parts. However, due to its limited formability at room temperature, titanium is typically warm formed. In the study, a new type of electro-assisted warm spin forming method based on the electroplasticity effect is presented. Experimental results show that electro-assisted forming technology can significantly improve forming quality of titanium parts. Advantages of the method include short forming times, uniform temperature distribution, simple operation, and convenient control. The influence of process parameters, including current intensity, feed rate, spindle speed, and lubrication, on the formability of commercial pure titanium sheets was systematically analyzed using an industrial spinning machine. It was found that deformation is mainly concentrated in the arc phase of the curved generatrix. Finally, components were subjected to uniaxial tensile stress and biaxial compressive stress based on previously defined forming limit curves. The technology is feasible and easy to control and has the potential for application to other rotary sheet forming technologies.

Keywords Electro-assisted spin forming · Joule heating · Strain analysis · Electroplasticity effect · Formability · Warm forming

1 Introduction

Spin forming is a near-net shape forming process that is used to produce seamless hollow axisymmetric prats. It offers controlled deformation conditions, tight tolerances, economical production, a wide range of part quantities, simple tooling, and high material utilization [1]. Spin forming can be used to produce parts from virtually all ductile metals but is increasingly being used for titanium and titanium alloy components which are widely used in including aerospace, defense, and medical applications [2].

Titanium has excellent strength, low density, and corrosion resistance but tends to have poor ductility at room temperature that can be accompanied by large springback, wrinkling, easily loose stability during forming, and components are more susceptible to cracking [3]. Consequently, warm or hot forming is often required to form titanium and titanium alloys. Temperature control is one of the most important factors affecting the quality of formed parts. If the forming temperature is too low, large resistance to deformation exists leading to poor plasticity and cracking, whereas if the temperature is too high, the metal is prone to galling and surface oxidation, reducing the overall quality of spun parts. Quality of spin formed parts is also affected by cyclic thermal stress, adhesion of the material to the mold, and lubrication [4].

The most common thermoforming methods used to fabricate titanium components include flame heating and electromagnetic induction heating. Of the two methods, flame heating is the most common method. However, with flame heating, workpieces are not heated uniformly and a large temperature gradient typically develops. Because titanium has poor thermal conductivity, deforming is uneven and the

✉ Xia Jin
meejxia@nuaa.edu.cn

[1] College of Mechanical and Electrical Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, People's Republic of China

[2] College of Material Science and Technology, Nanjing University of Aeronautics and Astronautics, Nanjing 211100, People's Republic of China

[3] Department of Mechanical Engineering, Marquette University, Milwaukee, WI 53005, USA

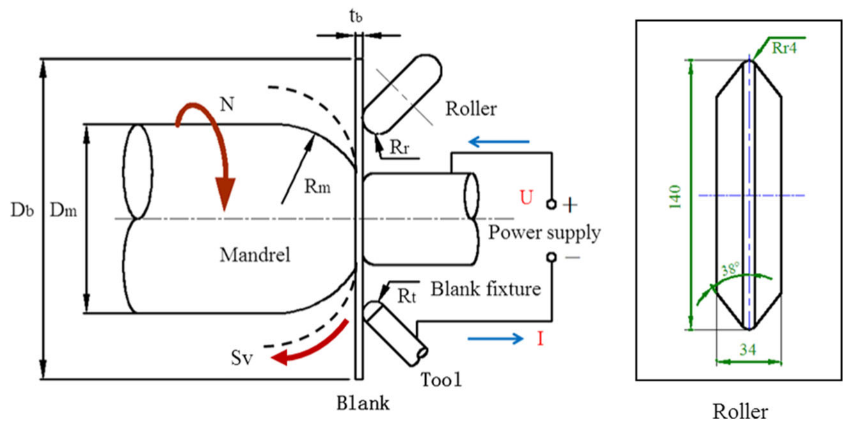


Fig. 1 Schematic of electro-assisted spinning

workpiece surface is prone to the formation of dense cracks [5]. Electromagnetic induction heating is rapid and offers a greater lever of control; however, the heating coil and power supply are more complex and are better suited for producing tubular parts rather than the highly variable contoured parts in the spinning forming process [6].

Conventional heating methods used in metal processing typically rely on external heat generation that is then transmitted to the workpiece surface, thus creating thermal gradients reducing thermal efficiency. In comparison, Joule or ohmic heating has the advantage of highly uniform heating as well as more precise temperature control. Furthermore, the effectiveness of Joule heating is directly related to the electrical resistivity of the material. Commercial pure titanium has an electrical resistivity of 48 Ω m at room temperature, which is 18.1 times greater than that of aluminum and 4.9 times that of iron. Resistivity tends to increase with increasing temperature. Direct current heating thus represents a suitable alternative for thermoforming titanium due to the high thermal resistance of the material. When there is direct current heating, composite electroplastic effects are caused by Joule heating, magnetic compression, pure electroplasticity, and skin effects [7–9]. The magnetic compression and skin effects have been shown to provide minimal contribution to reducing flow stress of the material. Only the pure electroplastic effect and Joule effect can influence the flow stress during plastic deformation of the material, and in this case, the Joule heating effect plays a key role [10–13]. Thus, electro-assisted forming has been used as a new forming method based on the composite electroplastic effect [14] and can improve the productivity, efficiency, and quality of parts compared to other forming methods [15–21].

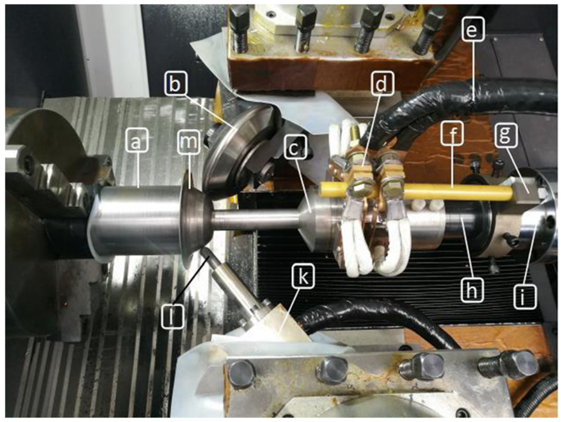
Table 1 Process parameters used to control the electro-assisted spinning

Symbol	Meaning	Value
N	Rotational speed	Variable
Dm	Mandrel diameter	80 mm
Db	Blank diameter	120 mm
tb	Blank thickness	1 mm
Sv	Roller feed	Variable
Rm	Mandrel nose radius	40 mm
Rt	Tool nose radius	6 mm
U	Voltage	0-15 V
I	Electric current	0–1500 A

A new incremental forming method based on electrical heating was initially proposed by Fan et al. [22]. In this study, the influence of current intensity, tool size, feed rate, and step length on the formability of AZ31 magnesium was investigated. Experimental results demonstrated that the technique was feasible and easy to control. Electro-assisted single-point incremental forming of Ti-6Al-4V has also been studied, and current was found to be the most critical factor affecting temperature. Using electro-assisted forming, an excellent composite structure with slender α-phase grains and basket weaving structure was obtained, and the surface was slightly oxidized [23, 24]. Furthermore, Honarpisheh et al. [25] used a combination of experimental methods and numerical simulations to study the incremental electro-assisted formability of Ti-6Al-4V. Results showed that incremental forming force increases with increasing step length and decreasing tool diameter. Thickness of the formed component decreases with increasing forming angle and decreasing step length. The forming force and thickness distribution were predicted using finite element simulations and simulated values were consistent with experimental results. Ross et al. [26] studied the tensile and compressive behavior of Ti-6Al-4V titanium alloy under direct current heating and found that the electric current

Table 2 Chemical composition of commercial pure titanium sheet

Main components (wt%)	Impurity composition (wt%)					
Titanium	Iron	Silicon	Carbon	Nitrogen	Hydrogen	Oxygen
Balance	0.3	0.15	0.1	0.05	0.015	0.2



a.Mandrel
b.Roller
c.Blank fixture
d.Carbon brush holder
e.Wire
f.Insulating rod
g.Fixed frame
h.Insulators
i.Mobile shaft
j.Power supply
k.Fixture
l.Tool heads
m.Titanium blank

Fig. 2 Photograph showing electro-assisted spin forming set-up used in the investigation

significantly improves formability of titanium alloys. Perkins et al. [27] performed compression experiments under direct current and found that significant stress softening occurs at lower current densities due to the high electrical resistivity of titanium alloys. Tensile tests were conducted by Magarge et al. [28] on commercial pure titanium using a combination of small-sized specimens and low-density currents. Under the same current density, the flow stress at high temperature was reduced by nearly 50% compared to unpowered tensile testing (no current).

To date, titanium electro-assisted forming has been successfully applied in rolling, drawing, bending, and superplastic forming. It has been shown to reduce the resistance to deformation of materials and improve mechanical properties of titanium alloys [29]. Basic research on electro-assisted incremental forming and drawing of titanium alloys has been carried out, but electro-assisted spin forming has yet to be applied to titanium alloys. In this study, the DC heating and spin forming technologies were combined to develop an electro-assisted spin forming method that can be used to produce axisymmetric titanium components.

2 Experimental setup and design

A schematic illustration of the electro-assisted spinning process for titanium sheets is shown in Fig. 1. Control parameters of electro-assisted spinning are shown in Table 1. While the process was developed for spinning titanium, it also has potential application for other hard to spin metals such as stainless steel and nickel alloys. Each spinning tool was securely mounted inside a fixture at a 45° angle to the workpiece centerline and was equipped with a compression spring to adjust the force. Two diametrically opposed rollers made from tungsten carbide (YG8) to ensure sufficient hardness and wear resistance at high temperatures were employed as the spinning tools. A high-frequency low-voltage power supply that has an output of high-energy low-voltage DC current was used. The titanium sheet was fixed between the blank fixture and mandrel. The blank fixture and tool were connected to the positive and negative poles of the power supply. A current loop was then formed between the power supply, blank fixture, titanium plate, and tool. Process-related geometric parameters and control parameters are also shown in Fig. 1.

Commercial pure titanium was used as the blank in this study and its composition is shown in Table 2. The titanium blank was 1.0 mm thick and 120 mm in diameter. The experimental material was obtained by laser cutting of a pure titanium sheet. Experiments were performed on a commercial CNC spinning machine (SXY600HD, Huizhou Bosai CNC Machine Tool Co., Ltd. China), which is shown in Fig. 2. The work zone and tools were insulated from the machine body using a silica gel plate. As the tool starts to move, it slowly makes contact with the work-piece. Then, the circuit current opens and the local temperature rapidly increases at the contact area. Due to rotation of the mandrel, the contact circle was heated rapidly. Heating and forming were synchronously performed by interworking of the roller and tool.

Therefore, one of the key objectives of this paper is to investigate the effects of the main parameters, listed in

Table 3 Electro-assisted spin forming process parameters

Process parameter	Value
Electric current intensity	200 A, 300 A, 400 A
Rotation rate by linear velocity	15 m/min, 20 m/min, 25 m/min, 30 m/min
Rotation rate by angular velocity	100 r/min
Feed rate in axial direction	0.5 mm/r, 1.0 mm/r, 1.5 mm/r, 50 mm/min, 100 mm/min
Lubrication	Molybdenum disulfide

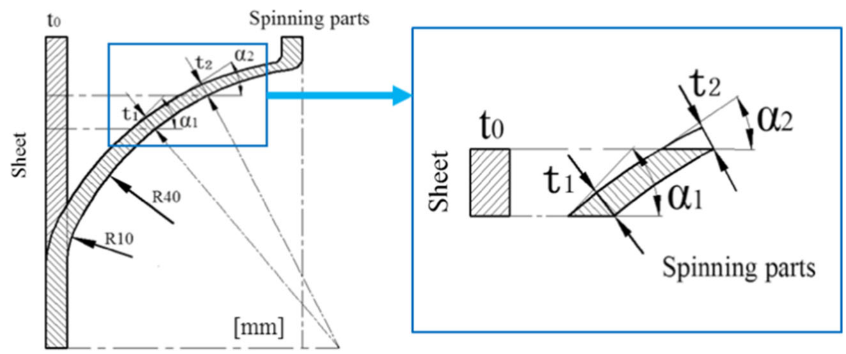


Fig. 3 Schematic diagram of the deformation contour

Table 3, to determine which are the most influential with respect to spin-forming of titanium components. Considering the relationship between current intensity and titanium sheet temperature as well as commercial pure titanium recrystallization temperature, we chose 200 A, 300 A, and 400 A to study the potential influence of current intensity on the forming properties of pure titanium. The metal sheet spinning feed rate is usually 0.1–1.5 mm/r [30]. Therefore, in the electro-assisted spinning process, 0.5 mm/r, 1.0 mm/r, and 1.5 mm/r were selected to study the spinning process of the titanium plate. The diameter of the components varies greatly along the axial direction. Therefore, constant linear velocity and constant angular velocity were both tested in this study.

Molybdenum disulfide was sprayed on the surface of the commercial pure titanium sheet to form a dense lubricating film. Molybdenum disulfide has good pressure resistance, a small friction coefficient (0.04 or less), good thermal stability, good lubricity at 400–500 °C, and exhibits excellent adhesion to metal surfaces. To analyze deformation characteristics and stress states during the spin forming process, an optical strain measurement system (ARGUS) was used. Strain grids were electrochemically etched onto the surface. The electrochemical corrosion spot is circular and its diameter is 1 mm, and the distance between the centers of two adjacent corrosion spots is 3 mm.

3 Analysis of deformation in electro-spin forming

Due to the fact that the diameter of the part differs from that of the starting blank, some changes in wall thickness are expected to occur. If spinning deformation of the curved busbar part is generated by shear, the thickness variation can be calculated according to the sine law [31]. Deviation in wall thickness can have a significant impact on the deformation state of titanium sheets and can be expressed by the wall thickness deviation rate Δt [6]:

$$\Delta t = \left({}^{t_a}/_{t_i} - 1\right) \times 100\% \tag{1}$$

where t_a is the actual thickness and t_i is the calculated thickness which can be obtained using the sine law as follows:

$$t_i = t_0 \sin \alpha_i \tag{2}$$

where t_0 is the initial thickness and α_i is the included angle with the tangent line, as shown in Fig. 3.

When the deviation is negative ($\Delta t < 0$), the thickness of the titanium sheet is drastically reduced and the material in the deformation zone mainly undergoes shear deformation. When there is a positive deviation ($\Delta t > 0$), the deformation mainly

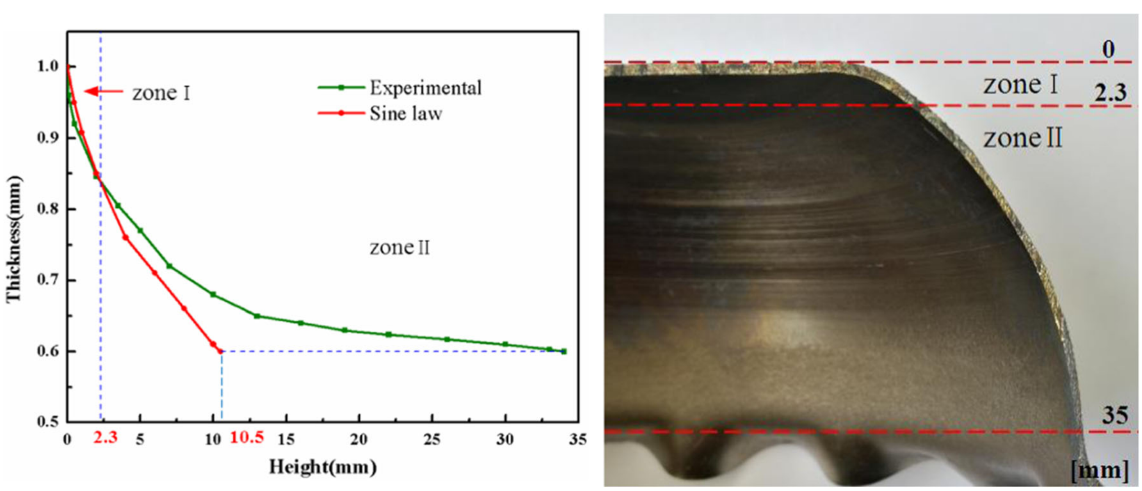


Fig. 4 Wall thickness distribution of spin-formed component

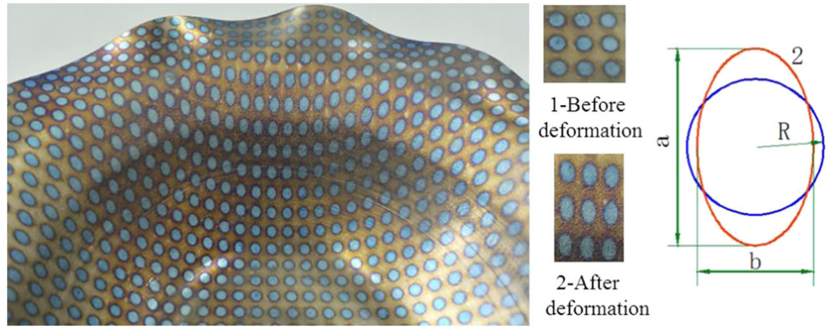


Fig. 5 Local images of strain grid before and after spin forming

consists of uniaxial tensile deformation due to the radial additional tensile stress. If the deviation is equal to zero ($\Delta t = 0$), the strain is changed from uniaxial stretching to shear.

In this study, electro-assisted spin forming of titanium sheets was performed using a current intensity of 400 A, feed rate of 0.5 mm/r, rotational speed of 25 m/min, and molybdenum disulfide lubricant. As shown in Fig. 4, the actual wall thickness distribution of the spin-formed component is consistent with the designed contour and two distinct zones can be identified. The wall thickness calculated according to the sine law is a theoretical and ideal result. Taking the commercial pure titanium thinning limit (45%) [6] into account, the maximum thickness reduction was designed to 40%. Due to the additional compressive stresses (zone I) and tensile stresses (zone II) in radial direction of the sheet, the wall thickness distribution obtained from experimental (Fig. 4) was a little bit different from theoretical calculation. The wall thickness deviation rate was negative and excessive thinning of the material was observed in zone I. This led to an increase in the resistance to forward flow of the material and part of the material was forced to flow backwards, resulting in reverse extrusion at the bottom of the part. An annular band of material was easily formed, as shown in Fig. 18a, c, d. As the amount of deformation increased, the wall thickness deviation rate became positive, as seen in zone II. Furthermore, if positive deviation increases gradually, inadequate thinning can easily lead to edge wrinkling. Therefore, reasonable process parameters can significantly improve the performance of the forming process when the thinning ratio of the wall thickness of the spinning part and the mounting angle of the rotating wheel remain unchanged.

The strain state, before and after spin forming, is shown in Fig. 5. In the deformed region, the circular grid marks were stretched into ellipses. Deformation of the grid became more evident as the amount of deformation increased. At the bottom of the part, no deformation occurred and the grid remained unchanged.

Based on the strain distributions shown in Fig. 6, it can be seen from that strain is mainly concentrated on the arc wall where the stress state can be considered uniaxial tension. A path from the center of the component to the edge was selected and the corresponding strain curves are shown in Fig. 7. The minor strain remained negative; therefore, compressive stress was shown to always act in this direction. At the beginning of spin forming, the major strain was equal to the minor strain and shear stress state played a dominant role. When the wall thickness deviation rate changed from negative to positive, the stress state was transformed into uniaxial tension. The strain increased to a peak in the major stress direction, maximum strain occurred in the section of length 36.8 mm, at which the point of the equivalent strain and major strain also reached a maximum. Here, the stress state can be approximated as the plane stress state. Ductile fracture is most likely to occur in this region. As the major strain decreased, the stress state was returned to uniaxial tension above the peak and material accumulated in the thickness direction. Due to the material pile

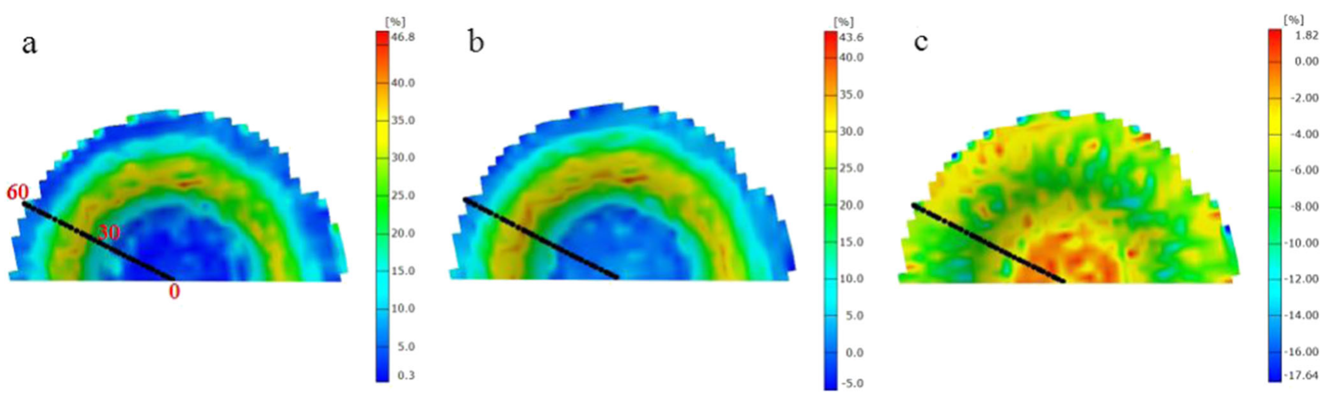


Fig. 6 Strain distribution after spin forming: **a** Mises strain, **b** major strain, **c** minor strain

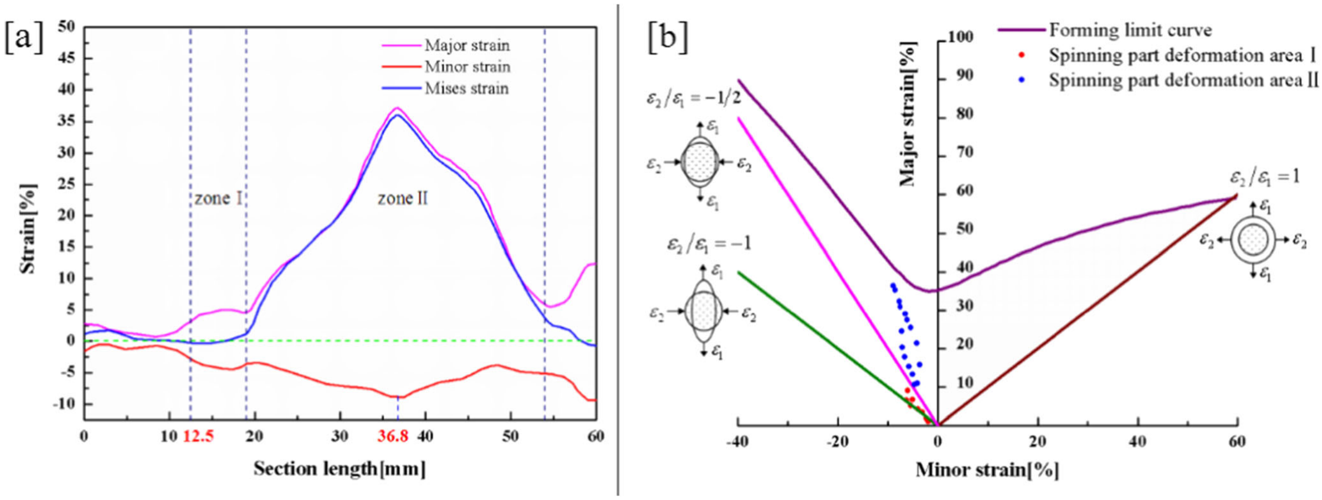


Fig. 7 Strain distribution curves of spun component: **a** strain distribution path, **b** strain distribution in forming limit curve

up and compression, wrinkle defects occurred at the free edge of the component.

In summary, if the wall thickness deviation rate Δt, presented in Eq. (1), is greater than zero, the primary stress state of the deformation region is uniaxial tension and biaxial compression. Therefore, the axial tensile stress and the radial compressive stress play dominant roles. The circumferential compressive stress has a limited effect. Moreover, if $\Delta t$is less than zero, the stress state becomes pure shear. To further clarify this phenomenon, the strain states of the path (Fig. 6) are shown on the forming limit curve [32] in Fig. 7. Thus, it can be deduced that the characteristic deformation of electro-assisted pure titanium spin forming is uniaxial tension and pure shear.

4 Effects of process parameters

4.1 Effect of electro-assisted heating

To assess the effect of the DC heating method on the spinning process, unassisted and electro-assisted tests were performed. In both cases, the linear velocity was set at 25 m/min and feed rate was 0.5 mm/r. In the electro-assisted case, 400-A direct current was used. Forming results are shown in Fig. 8. At room temperature, pure titanium has large deformation resistance and spring-back, and it is difficult to spin to obtain parts with precise shape and size. When a high-energy DC current of 400 A was applied, the temperature of the sheet rose to about 400–500 °C, which is a warm forming process since the recrystallization temperature of commercial pure titanium is 550–650 °C [33] .

Very little difference was observed between the contour of the component obtained using the electro-assisted method and the contour of the mandrel, as shown in Fig. 9. Compared with the spinning part formed at room temperature, the forming height of the current-assisted spinning part is increased by 65%. Therefore, formability is significantly improved by using the electro-assisted heating method.

4.2 Effect of lubrication

Friction is one of the important factors influencing sheet metal forming, affecting not only the processing force and energy consumed, but also directly influencing the forming limit,

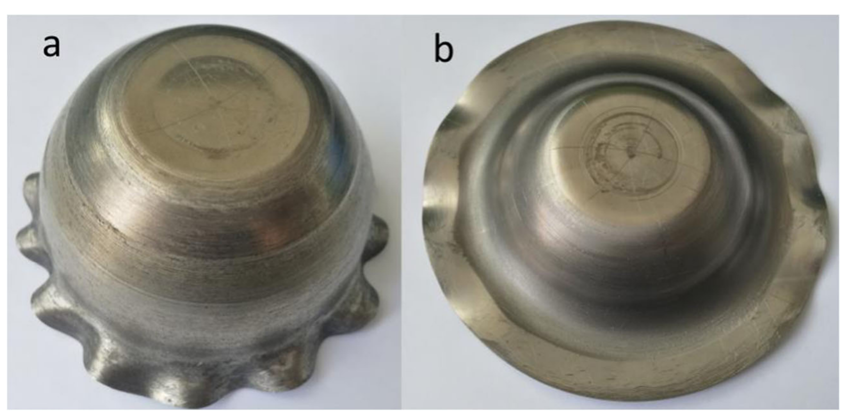


Fig. 8 Spin formed components obtained using: **a** electro-assisted thermoforming; **b** room temperature forming

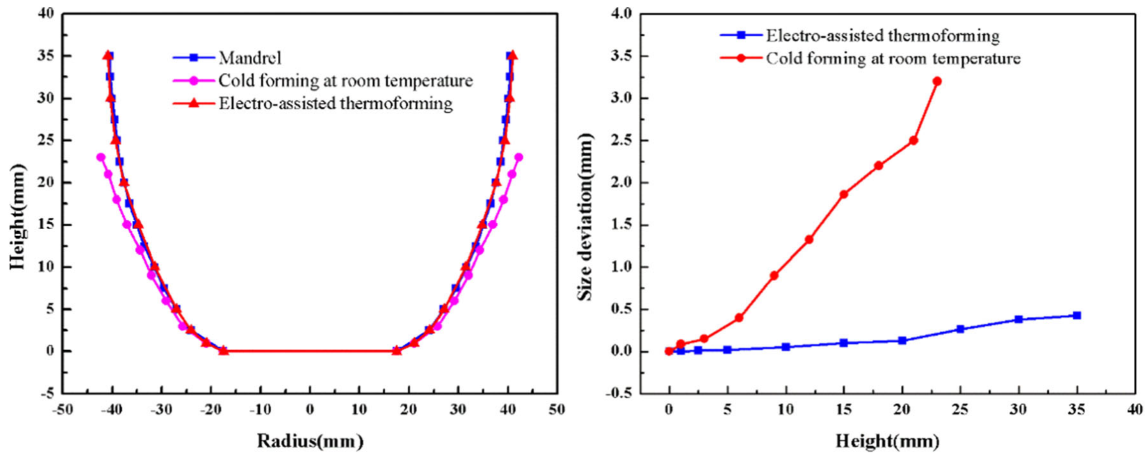


Fig. 9 Comparison of contour and size deviation between electro-assisted thermoforming and cold forming at room temperature

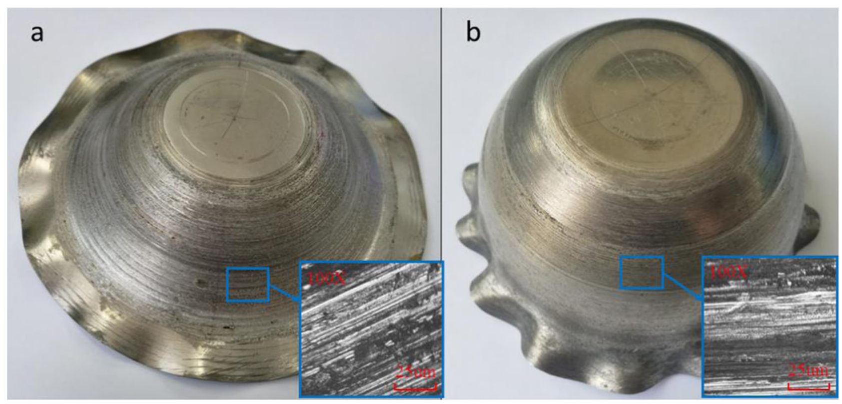


Fig. 10 Titanium components spin formed using **a** no lubrication and **b** molybdenum disulfide lubricant

springback, and surface quality of the workpiece [34]. Friction is generated during the electro-assisted spin forming process due to high local pressure, electric conduction, and the high temperature environment. The majority of friction is due to adhesive wear.

For blanks formed without lubrication, final components exhibited large surface roughness and poor formability, as shown in Fig. 10a. When the blank was in contact with the electro-assisted tool, the metal was softened rapidly and tended to adhere to the tool and roller under high temperature and high pressure. As a result of adhesion, small pieces of metal were torn from the surface resulting in the formation of pits. Rotation of the mandrel caused pits to accumulate in the circumferential direction leading to grooves on the surface. Thus, the surface became rough and uneven. Therefore, contact between the electro-assisted tool and blank surface also

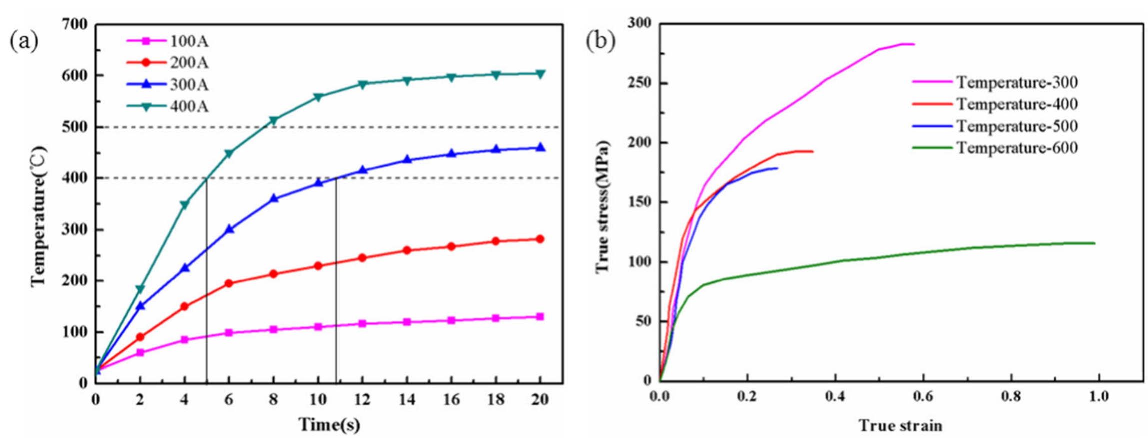


Fig. 11 **a** The relationship between temperature and current value and time. **b** True stress-strain curve of commercial pure titanium at different temperatures with a strain rate of 0.1 s^{-1}

Fig. 12 Titanium component spin formed under different current intensities: **a** 200 A, **b** 300 A, **c** 400 A

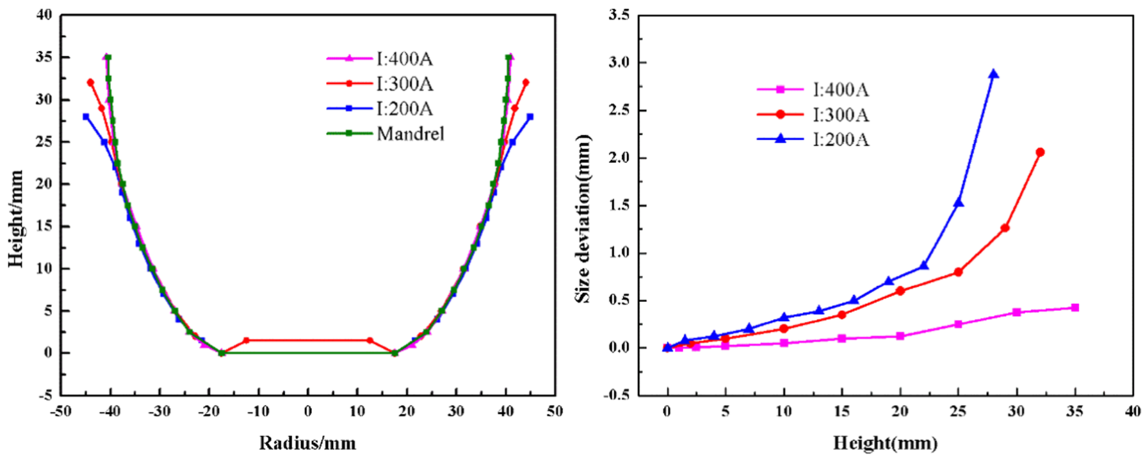


Fig. 13 Comparison of contours and size deviation at different current values

became uneven and a smaller region was in contact with the tool. Moreover, electric current concentrates in contact regions leading to heat concentrations. This causes more pits to form resulting in additional grooves, increased surface roughness, and poor formability.

Therefore, it is an ideal lubricant for electro-assisted spin forming. After spraying molybdenum disulfide lubricant on the blank surface, surface roughness and formability clearly improved, as shown in Fig. 10b. However, as the abrasion and temperature increased, lubricant was removed from the surface and small scratches began to appear.

By comparison with the roughness template, the surface roughness of the part without lubricant was above Ra200 μm and the surface roughness of the part coated with the lubricant is approximately Ra50–100 μm. It can be clearly seen under a 100× optical microscope (Fig. 10) that the surface without lubricant was uneven and had many grooves. Nonetheless, lubricant adhering to surface reduced surface roughness and lubrication is therefore a key process parameter.

4.3 Effect of current intensity

In electro-assisted spin forming, electric current can reduce the yield stress and flow stress and increase ductility of the titanium sheet due to the Joule heating effect, represented by

$$Q = I^2 \cdot R \cdot T \qquad (3)$$

where I is the current intensity, R is the specific resistance, and T is the heating time.

Thus, based on eq. (3), it can be seen from that a larger current intensity produces higher temperatures. Furthermore,

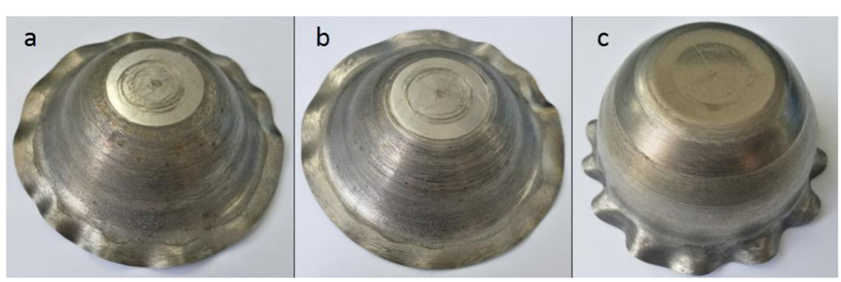


Fig. 14 Titanium component spin formed at different rotational speed modes: **a** angular velocity of 100 r/min, feed rate of 50 mm/min. **b** Angular velocity of 100 r/min, feed rate of 100 mm/min. **c** Linear velocity of 25 m/min, feed rate of 0.5 mm/r

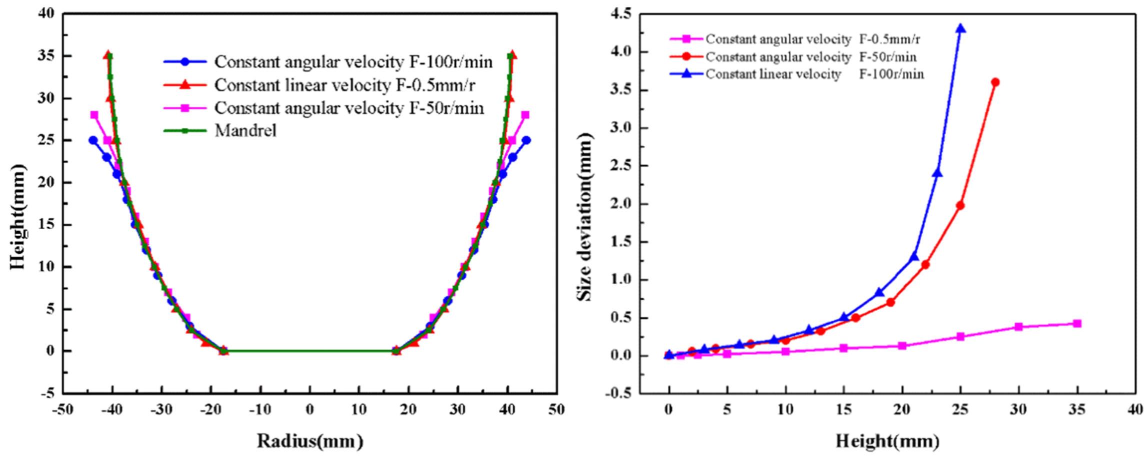


Fig. 15 Comparison of contour and size deviation at different rotational speed modes

based on the fact that the specific resistivity of commercial pure titanium increases with increasing temperature, at different current outputs, the relationship between the time and local temperature of the titanium plate is shown in Fig. 11a. With the increase of the current output time, the local temperature of the titanium plate rapidly increases and then gradually becomes stable. The optimal temperature range for commercial pure titanium forming is from 400 to 500 °C. Therefore, the most suitable forming current for commercial titanium plates is 400 A, and the heating time is fast. The intensity of the current affects the sheet temperature, and the mechanical properties of titanium are influenced by the temperature. The true stress-strain curve of titanium at different temperatures has been added into our article as shown in the Fig. 11b.

Based on the pure electroplastic effect, larger current intensity causes drift electrons to increase thrust on dislocations to overcome deformation obstacles [35]. Observing Fig. 12 and Fig. 13, the current intensity has a significant effect on the forming process. As current intensity increased, formability and size accuracy improved. In addition, decreasing current intensity resulted in earlier wrinkling.

Fig. 16 Titanium components spin formed at linear speeds of **a** 30 m/min, **b** 25 m/min, **c** 20 m/min, **d** 15 m/min

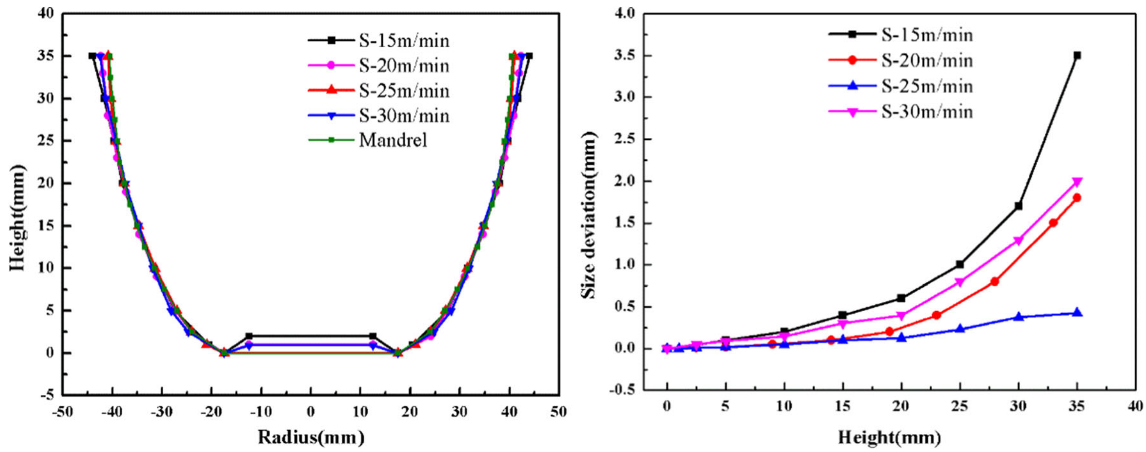


Fig. 17 Comparison of contour and size deviation at different linear velocities

4.4 Effect of rotational speed

To investigate the effect of rotational speed, in this study, constant linear velocity and constant angular velocity were both tested. The diameter of the component becomes larger and larger along the axial direction. The rotational speed can be given as a constant linear velocity or constant angular velocity and at the contact area. It will have a certain influence on the force and temperature distribution.

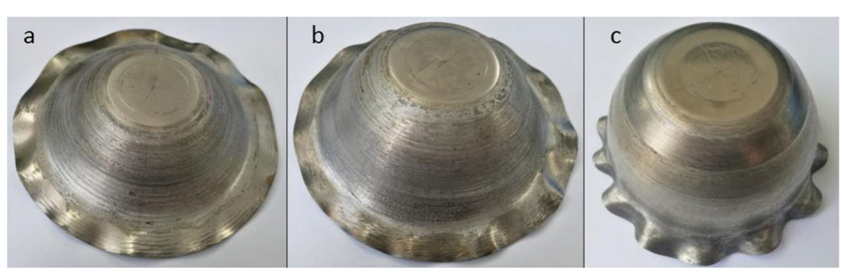
When the rotational speed was given as constant angular velocity, the contact speed between the roller and workpiece increased as the radius of the component varied. The changing contact speed led to inconsistent local temperature at the contact area, resulting in an uneven temperature distribution. As shown in Fig. 14a, b, plastic instabilities can clearly be seen and spin forming became more difficult. When a constant linear velocity was adopted as the rotational speed, formability was significantly improved, as shown in Fig. 14c. Since the contact speed remains unchanged, the temperature distribution is uniform, leading to homogeneous deformation. For the constant linear velocity, spin-formed components had smaller size deviations (Fig. 15). Therefore, a constant angular velocity should be adopted as the rotational speed during electro-assisted spin forming.

Regardless of rotational speed used, no significant influence on formability was observed during room temperature spin forming. However, a close relationship between linear velocity and local contact temperature distribution was observed in this study. Further, constant linear velocities were set at 15 m/min, 20 m/min, 25 m/min, and 30 m/min to study the effect of velocity on spin forming. The respective spin formed components are shown in Fig. 16. Contours and size deviations are depicted in Fig. 17. No obvious differences are observed in the deformation zone; however, wrinkling defects appear at the edge. Moreover, an optimal linear velocity was found to exist, as shown in Fig. 17. Using constant linear velocities of 15 m/min, 20 m/min, and 25 m/min, size deviations were shown to continuously decrease along the axial direction. However, the linear velocity (30 m/min) showed an abnormal trend. A large linear velocity (30 m/min) led to a slower local temperature increment. Thus, the formability of the sheet decreased. In addition, the sprayed molybdenum disulfide on the surface was worn off under the large velocity. Therefore, an optimal speed parameter(25 m/min) is required to obtain reliable products in electro-assisted spin forming.

4.5 Effect of feed rate along axis direction

The feed rate of the roller has a significant influence on deformation in room temperature spin forming [36]. To verify the effect of feed rate in electro-assisted spin forming, feed rates of 0.5 mm/r, 1.0 mm/r, and 1.5 mm/r were set. Experimental results showed that when the feed rate is relatively small (0.5 mm/r), local temperatures increased rapidly. Titanium sheets were clearly softened, leading to improved plastic deformability, as shown in Fig. 18c. In contrast, plastic

Fig. 18 Titanium components spin formed at different feed rates: **a** 1.5 mm/r, **b** 1.0 mm/r, **c** 0.5 mm/r



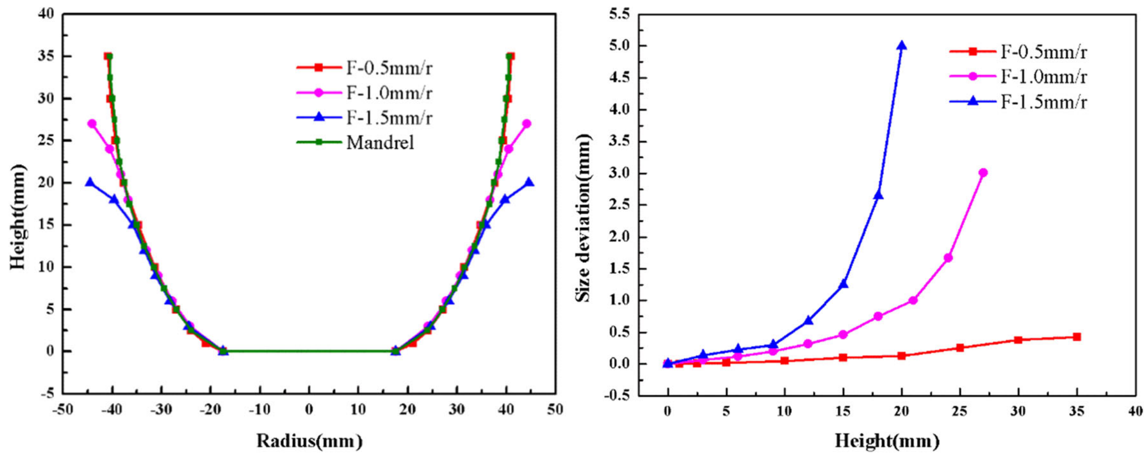


Fig. 19 Comparison of contour and size deviation for different feed rates

deformability of the titanium sheet was reduced as feed rate increased. Since the forming limit is significantly reduced, wrinkling defects occur earlier. Moreover, surface roughness is also reduced and scratches appear, as shown in Fig. 18a, b. Maximum size deviation was observed at a feed rate of 1.5 mm/r, which is 12.5 times larger than the component formed at a rate of 0.5 mm/r, as shown in Fig. 19. Therefore, higher feed rates result in larger size deviations. At the same time, defects like bell mouth shape and wrinkling occur more easily. Thus, it can be concluded that adopting smaller feed rates results in improved plastic properties and surface quality for titanium parts.

5 Summary and conclusion

In the present study, DC heating and spin forming were combined to form a new process termed electro-spin forming. The forming mechanism was analyzed and the influence of key process parameters including current intensity, linear velocity, feed rate, and lubrication on forming process and performance of pure titanium plates was studied. Based on the results obtained, the following conclusions can be made.

(1) Compared to room temperature spin forming, electro-assisted spin forming greatly improves the formability of titanium as it significantly increases the forming limit and reduces springback.

(2) During electro-assisted spin forming, thickness deviation rate is an important parameter for verifying the thickness variation designed by the sine law. If the rate is negative, the stress state is pure shear. If the rate is positive, the stress state becomes uniaxial tension; moreover, axial tensile stress and radial compressive stress play dominant roles. Circumferential compressive stress has little effect on the process. Controlling the thickness deviation rate to within a suitable range can effectively avoid defects caused by reverse extrusion, bulging, and wrinkling.

(3) Lubrication was found to be an important parameter that affects surface topography and current flow in the titanium sheet. Molybdenum disulfide was found to be a suitable lubricant for electro-assisted spin forming and can effectively reduce roller wear while improving the quality of the formed surface.

(4) In contrast to room temperature spin forming, the rotational speed was found to have a significant influence on quality of the formed component. Results of the experiments have shown that using a constant linear velocity can form better components. Also, current intensity and feed rate have obvious effects on the spin forming process and performance of spin formed titanium sheets. Increasing the applied current intensity leads to improved plastic deformability. Finally, smaller feed rates result in better surface quality.

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