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# Advances and Trends on Tube Bending Forming Technologies

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**Abstract**

As one kind of key components with enormous quantities and diversities, the bent tube parts satisfy the increasing needs for lightweight and high-strength product from both materials and structure aspects. The bent tubes have been widely used in many high-end industries such as aviation, aerospace, shipbuilding, automobile, energy and health care. The tube bending has become one of the key manufacturing technologies for lightweight product forming. Via the analysis of bending characteristics and multiple defects, advances on exploring the common issues in tube bending are summarized regarding wrinkling instability at the intrados, wall thinning (cracking) at the extrados, springback phenomenon, cross-section deformation, forming limit and process/ tooling design/optimization. Some currently developed bending techniques are reviewed in terms of their advantages and limitations. Finally, in view of the urgent requirements of high-performance complex bent tube components with difficult-to-deform and lightweight materials in aviation and aerospace fields, the development trends and corresponding challenges are presented for realizing the precise and high-efficiency tube bending deformation.

*Keywords:* tube bending; forming; lightweight; high strength; defects; aviation; aerospace

## 1. Introduction

As one kind of key lightweight components for "bleeding" transforming and loading carrying with enormous quantities and diversities, metallic bent tubular parts have attracted increasing applications in many high-technological industries such as aviation (shown in Fig. 1), aerospace, shipbuilding, automobile, energy and health care since they satisfy the current needs for products with lightweight, high strength and high performance from both materials and structure aspects. To bend the tubular materials with certain bending radius, bending angle and shapes, the tube bending, one important branch of the tubular plastic forming fields, has been a vital manufacturing technology for lightweight products urgently needed in the above industries [1-2].

Many tube bending approaches have been developed in response to the diverse demands of tube specification, shapes, materials and forming tolerance [3-4]. According to the forming conditions, there are cold bending at room temperature and hot (heat) bending with elevated temperature. From the viewpoint of loading conditions, there are pure bending, compression bending, stretch bending, roll bending, rotary draw bending and laser bending. There are stainless steel tube bending, aluminum alloy tube bending, copper tube bending, magnesium alloy tube bending and titanium alloy tube bending in materials point of views. From aspects of tubular shapes, there

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are round tube bending, rectangular tube bending and other irregular section tube bending. There are seamless tube bending and welded tube bending from the tube fabrication respect. From the viewpoint of bending difficulty, there are easy bending with large bending radius and tough bending with small bending radius. For any bending process, upon bending deformation, the complex uneven tension and compression stress distributions are induced at the extrados and intrados of bending tube respectively, which may cause multiple defects or instabilities such as wrinkling, over thinning (cracking), cross-section distortion and springback, etc (shown in Fig. 2). The accurate prediction and efficient controlling of these physical phenomena are the ever existing knots in forming manufacturing field including tube forming, also the research focus on a global scale [5-8].

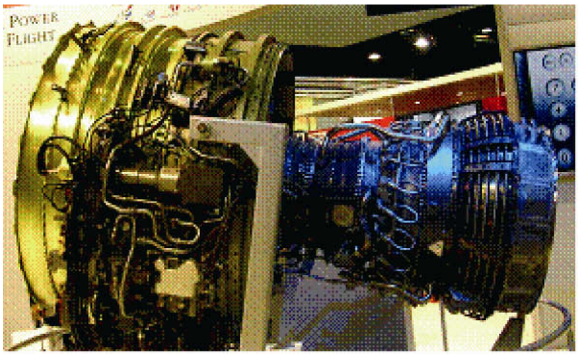



Fig. 1 Demonstration of bent tube application as "bleeding" transforming function in aeroengine [9].

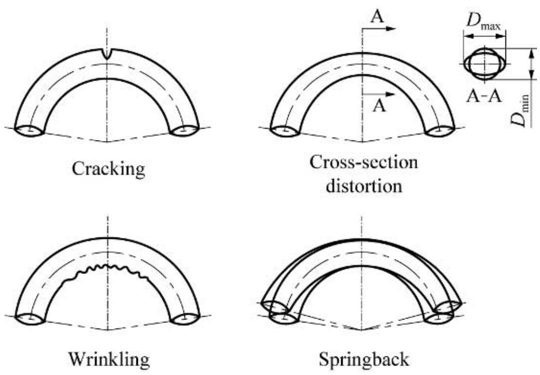



Fig. 2 Multiple defects or instabilities [9].

Up to now, regarding different tube bending processes with various loading conditions, great efforts have been conducted on investigations of the multiple defects/instabilities, selection/optimization of the forming parameters and tooling to promote the development of tube bending science and technology by using analytical, physical experimental and numerical methods. In recent years, along with the further requirements of the forming quality and bending limit for lightweight, high strength and high performance bent tube components in aviation and aerospace industries, new challenges are brought to the product design of bending tube, control of the multiple instabilities, improvements of the forming limit and technical equipment. Thus the corresponding theories and technologies should be urgently resolved.

In view of the above requirements and bending characteristics, advances and the existing problems on investigating the common basic topics in tube bending are addressed such as wrinkling instability, over thinning (even cracking), cross-section deformation and springback phenomenon. Also the currently developed tube bending techniques are reviewed in terms of their advantages and limitations. In light of the current demands of precision and high-efficiency bending forming for high performance bent tube components with lightweight and difficult-to-deform materials in aviation and aerospace fields, the development trends and difficulties urgently needed to be solved are addressed.

## 2. Progress of Tube Bending Theory

The occurring mechanisms, accurate prediction and efficient controlling of multiple defects/instabilities are the core contexts in the study of tube bending theory. The precise bending depends on the in-depth insights on these bending phenomena as well as forming limits and tooling/process design.

### *2.1. Wrinkling instabilities*

During bending, the inner wall of tube thickens with in-plane double compressive stresses, and to some critical extent, the wrinkling instability may occur, which not only reduces the tube's strength, stiffness and fatigue life, but also determines the forming limit and bending quality, even makes the tooling wear and damage as well as the process interrupt [9-10]. Based on the knowledge about the wrinkling occurring of thin walled sheet metal forming, many studies have been carried out on the wrinkling of tube bending in terms of the occurring conditions, influential factors, prediction and control for different bending processes.

The experimental study into the plastic buckling of both stainless steel and aluminum alloy tubes subjected to pure bending was reported and found that the maximum principle strains with wrinkling occurring lie within 30% of those predicted by J2 deformation theory, less than those by J2 flow theory [11]. By analysis, the wrinkling phenomenon in aluminum alloy tube under pure bending was solved [12]. The prebifurcation solution was considered uniform along the length of the tube, and the onset of wrinkling was predicted by introducing a sinusoidal buckling mode as imperfection. The flow theory of plasticity with isotropic hardening was used for the prebuckling solution, while the bifurcation check was based on the incremental moduli of a finite strain deformation theory of plasticity. Compared with the prediction results from the shell theory approximations, it was found that the three-dimensional continuum theory predicted slightly shorter critical wrinkling wavelengths, especially for lower diameter-to-wall thickness ratios.

Since the wrinkling is interactively affected by so many factors such as material properties, geometrical dimensions, loading patterns and especially contact conditions [9,13], merely the analytical theory and the experimental approach cannot be used to thoroughly and efficiently reveal the wrinkling mechanisms and provide accurate prediction. Considering the characteristics of the multiple tooling constraints of rotary draw bending, by using the minimum energy principle combined with analytical and finite element (FE) methods, an energy-based wrinkling prediction model for thin-walled tube bending is developed, in which a segment shell model, as shown in Fig. 3, was proposed to capture the critical wrinkling region [14-19]. It was found that the friction and clearance between tube and tooling as well as the mandrel parameters are the key factors for wrinkling avoiding, and the "stepped mandrel retraction" method was proposed to avoid the wrinkling in bending with small bending radii. The multiform and asymmetric local distribution features of the wrinkling were revealed. To avoid the wrinkling onset, the effect of the Archimedes parameter on the thermal pushing of Ti bending tube was studied and the suitable Archimedes parameter was obtained [20].

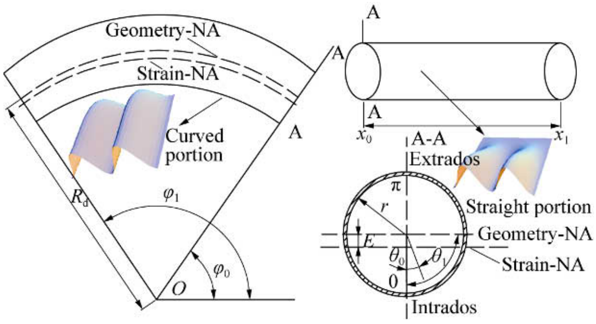



Fig. 3 Segment shell model for wrinkling prediction in NC tube bending process [16].

Nowadays, despite of the obtained knowledge on the compressive instability, the avoiding of this instability is still the bottleneck for improving the bending limit and achieving the precision bending deformation, especially for tube bending with large diameter and small bending radius. References [21]-[22] showed that the wrinkling tendency increases with larger tube diameter and larger area of the critical wrinkling region, thus more strict cooperation of multiple tooling is needed due to the sensitive effects of the contact conditions on wrinkling onset.

### 2.2. *Wall thinning and cross-section deformation*

Upon bending deformation, there are inevitable deformation phenomena including wall thinning at the extrados and wall thickening at the intrados along with the certain cross-section deformation (even distortion). The wall thinning degree directly affects the pressure resistance of bent tube, while the section flattening influences the flow resistance within the transmission medium and thus reduces the reliability of the tubular components. So, both the wall thinning and section ovalization degrees should be strictly controlled and the cracking and the section distortion should be avoided. Many scholars have undertaken the extensive research to obtain the theories and methods for prediction and controlling of the wall thinning and cross-section deformation, which determines the bending accuracy greatly.

According to the geometrical characteristics and the plastic deformation theory, some practical formulae were deduced to solve the seven common tube bending issues including stress/strain distributions in the bend, wall thickness change, section shrinking rate, deviation of neutral axis, feed preparation length of the bend, bending moment and flattening [23]. However, due to many assumptions and simplifications, the accuracy and practical applicability are limited. Based on the stress formulae [23], the cross-section distortion and the wall thickness change of tubes under axial force and internal pressure were developed [24]. Both the experimental and analytical methods were employed to study the wall thinning and section ovalization of the small-diameter 1Cr18Ni9Ti stainless steel tube under bending process without mandrel [25-28]. By using the regression analysis, the empirical formula was fitted to calculate the wall thinning degree of the bending process without mandrel based on a lot of experimental data [29].

Regarding the 1Cr18Ni9Ti stainless steel and 5052O aluminum alloy tubes with size factor $D/t$ ($D$ is the diameter, $t$ is the thin wall thickness) of 38 and 50, the effects of various forming parameters on wall thinning and cross-section deformation were experimenttally addressed including the number of mandrel balls, mandrel extension length, bending angle, lubricants between tube and tooling, the pushing assistant velocity of pressure die, bending radius and material properties [30-35]. It was found that the hoop strain of the aluminum alloy tube under small bending radii cannot be neglected, and the over thinning and flattening of the aluminum alloy tube were prone to occur compared with the stainless steel tube. In the experiment, the grid method is used to be an effective method to measure the strain distribution and metal flow states of the bending tube.

The simulation on the prebending for hydroforming used to form an automotive part, a tie bar, was performed to obtain the shape change of the cross-section and the wall thinning of the tube bending [36]. The prebending was the rotary draw bending and die compression bending. Based on the Abaqus platform, both the wall thinning and section ovalization of the aluminum alloy and stainless steel tubes were numerically investigated [37-38]. Also, the FE simulation was conducted on pipe bending process with large diameter using local heating to calculate the wall thinning [39].

The above achievements on wall thinning and section flattening of bending tube provide theoretical guidance for improving the bending quality and forming limit. Both phenomena cannot be avoided as wrinkling instability, while they can be controlled within the tolerance by modifying the forming conditions.

### 2.3. Springback

The inevitable elastic release phenomenon with different degrees occurs when the tooling is removed due to the extrados elongation deformation and intrados compression deformation, which results in the decreased bending angle and the increased bending radius. The springback affects both the geometrical and shape precision, which directly determines the connection and sealing performance of tubes with other parts as well as the internal structure compact. Similar to the wrinkling instability, the springback phenomenon is all the time one of the key factors restraining the bending quality and increasing the cost of both the die and product as well as weakening the manufacturing efficiency [40]. Considering the beam bending theory and ignoring the wrinkling, cracking and bauschinger effects, the analytical formulae were derived for predicting the springback behavior and residual stress distributions with the assumption of the ideal elastic-plastic theory, unchangeable tube diameter and symmetrical section in the bending [41-42]. The coordinate experimental method was also used to analyze the springback and residual stress. Comparisons between theoretical and experimental results of springback have shown the remarkable agreement.

The theoretical and experimental study on spring back in rotary draw bending was conducted [43-44]. The study shows that the springback angle has linear relationship with the bending angle when the bending angle is larger, and the bend-rebend control is used to obtain the springback data and compensate for it on line. A process control method is developed to optimize the overall control strategy. Though the experiment-based springback prediction is relative reliable, the obtained springback data is only suitable for the tube bending with the same forming conditions.

Based on the tube bending theories and experiments, the empirical formulae were obtained to determine the springback (including angular springback and radius growth) and the stretching [45]. The effects of the forming parameters on the springback angle of thin-walled tube bending were analyzed by using the analytical model and experimental method [46].

Considering the relationship between bending moment and bending curvature, the springback angle was deduced [47-49]. However, due to the difficulty in considering the material properties (as shown in Fig. 4), geometrical dimensions and friction conditions simultaneously as well as neglecting the three-dimensional stress/strain, the purely analytically predicted results deviate from the experiments greatly.

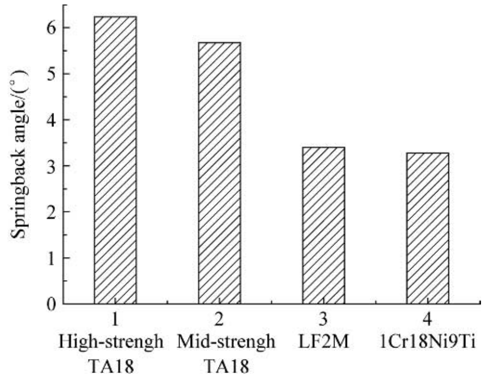



Fig. 4 Springback angles with different materials.

For the past few years, combined with the experimental and analytical methods, the FE numerical simulation is the primary tool to deeply analyze the springback of tube bending.

By using the FE simulation combined with the experimental research, it was found that the hardening exponent has little effect on the springback with the tube diameter and relative bending radius *D*/*t* unchanged [50]. Reference [51] observed that the timedependent springback happens at room temperature for some high strength stainless steel tube in rotary draw bending, while this phenomenon does not occur for other tubular materials such as DQSK, AKDQ and HSLA.

The numerical-analytical method was used to rapidly calculate the springback angle of thin-walled tube in rotary draw bending [52-53]. Via the numerical simulation of the whole process including tube bending, mandrel retracting and unloading [54], it was found that the total springback angle considering mandrel retracting was much smaller than that not considering mandrel retracting with maximum difference between them being 107.34%, and the total springback angle increases linearly with the increase of the bending angle when the bending angle is large. Numerical study on the coupling effects of the material properties such as elastic modulus, yield stress, strain hardening exponent and normal anisotropic coefficient on the spring back angle was done regarding mid-strengh TA18 (TA18M) tube bending of 14 mm × 1.35 mm [55-56]. Both the experimental and analytical methods were used to analyze the remarkable time dependent springback of 1Cr18Ni9Ti stainless steel tubes in rotary draw bending [57]. It was found that the time-dependent springback angle was more remarkable with the increase in the bending radius.

The above results are helpful to the realization of the precision tube bending. However, up to now, the efficient control of the springback is still solved by the experience and experiments. The springback is affected by so many factors that the variation of the springback is obvious and the accurate prediction of the FE simulation is difficult to be achieved.

### 2.4. Forming limit of tube bending

The difficulty for improving tube bending limit is attributed to the fact that there are multiple defects and coupling effects of multiple forming parameters. Especially, the method for reducing one instability should cause another defect to be much severer. Based on the understanding of the individual defect, to obtain the bending limit of tube with different material types and specifications is nowadays one hot and scabrous issue.

An energy approach-based minimum bending radius, which does no yield wrinkling in rotary draw bending, was presented as a function of tube and tooling geometry and material properties. A double-curved sheet model is used following the deformation theory [58]. Based on several experiments, the wall thickness distribution was analyzed and the minimum relative bending radius limited by wall thinning was obtained [27]. The bending limit of both aluminum square and circle tubes in rotary draw bending was studied [59-60]. The suppression effects of the rigid arcwise mandrel on the wrinkling and cross-section distortion were analyzed, also the influence of the forming parameters (clamping force, pressure die force, pushing assistant force and bending speed) on the wall thickness change and cross-sectional flattening were addressed. Combined with the analytical discussion, the comprehensive experimental study was conducted on the effects of various processing parameters on bending quality for 38 mm×1.0 mm of 5052O aluminum alloy tube considering both the wall thinning and cross-section deformation [61]. The processing parameters include the clearance and friction, mandrel extension length, bending angle and the number of mandrel balls.

Considering the wrinkling instability, wall thinning and cross-section deformation simultaneously, using the FE simulation and energy-based wrinkling predicttion model [9,62-64], a search algorithm of the forming limits (the minimum bending radii) in NC bending of Al-alloy tube with large diameters was proposed. The bent tubes with diameter larger than 100 mm and relative bending radii of 1.5 were successfully obtained (as shown in Fig. 5). Using FE simulation, the interactive effects of the material properties, contact conditions, pushing assistant velocity and mandrel parameters on wrinkling, cross-sectional deformation, wall thinning and springback were explored [30-31,37-38,65]. It was found that the larger friction at tube-pressure die and tube- clamp die improves the bending quality, while the larger friction at tube-wiper die and tube-mandrel reduces the bending limit.

According to the bending characteristics of 5052O Al-alloy tube with 50 mm × 1 mm and 75 mm × 1.5 mm [66], taking the wrinkling and wall thinning as the indices, the bending limits (including critical radius and critical bending angle) were obtained, respectively. Based on the knowledge about the wall thickness changing and section flattening, the bending limit under aeronautics specification for TA18M Ti-alloy tube of 14 mm×1.35 mm was determined and the tube specimens were bent [55]. The axial compressive loads were applied to the Al-alloy tube to improve the bending quality and the forming limit [67]. The influences of the internal pressure and friction on the pushing bending were numerically studied [68]. It was concluded that the relative smaller bending radius of 1.0 can be achieved with reasonable international pressure and lubricant conditions.


Fig. 5 Experimental bent tubes with large diameter.

Despite of the existing knowledge on defects, the bending limit of tube is still mainly established by the single defect based on empirical and analytical methods. With the increasing needs for high tolerance, the forming limit of tube bending should be obtained considering the multiple defects to facilitate the tubular product/bending process pre-design.

### 2.5. Process/tooling optimization/design

Due to the complexity of the tube bending with multiple defects and factors, the process/tooling optimization is a multi-object problem with multiple constraints from mathematical viewpoint. In practice, the empirical data or operator-based "trial and error" is still the major approach to obtain the feasible bending parameters [3-4]. This method may be applicable for the relative simple tube bending processes with small diameter, thick wall and large diameter as well as loose tolerance of bending quality. For precise tube bending with tough bending radius and difficult-to-deform tubular materials, the above method is not sufficient. However, the empirical data can provide rules for initial value determination in optimization process [69].

Using the object-oriented programming techniques and the goal-driven search mechanism, a knowledge-based system (KBS) was developed to aid the design of tube bending including bending methods selection, tool/die design and process parameter setup [70]. The system showed effectiveness in tube bending production with significantly reduced number of potential defects and failures. However, the knowledge is the empirical data, which is insufficient for tough bending conditions with small bending radii.

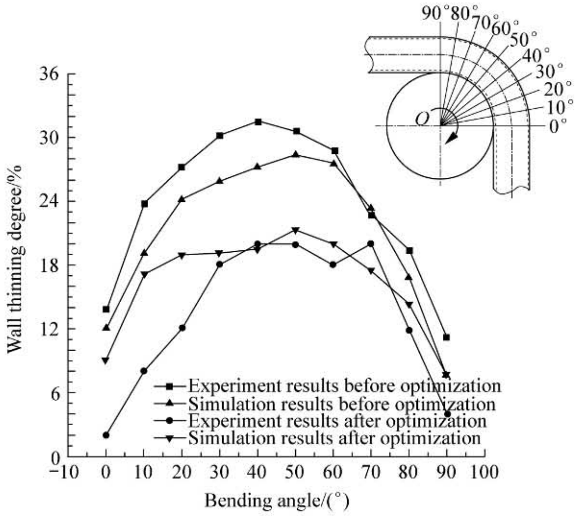
A computer-based tooling and process design methodology—Tube ProDes is proposed for rotary draw bending tooling design [71]. First, numerical calculations were performed to compensate for springback, and then by evaluating the severity of the bend ( i.e. the risk of the occurrence of defects) and assessing the sensitivity of the process with variations of the materials properties, the tooling setup was designed by fuzzy logic according to the material properties, the geometrical data of the bend and the variables previously calculated as input. While the processing parameters were not considered, neither of the selection results were totally dependent on a great quality of experimental data or empirical formulae about steel tube. Thus the design reliability is low with undesirable effectiveness and applicability. Based on generic CAD-models driven by heuristic and algorithmic knowledge, an automated tooling design approach and manufacturability analyses for rotary draw bending were developed to shorten the lead-time and improve the product performance [72]. The knowledge is collected and stored in central systems, thus allowing full control over the design of production. Whether the design is feasible can only be confirmed after the tooling try.

Considering the main geometrical data (thickness, outer diameter, bending radius and bending angle) and the strain distribution in a rotary draw bending, an algorithm generated the right correlation between the booster and the pressure die velocity curves [73]. The influences of the mandrel parameters (with or without flexible balls) on the bending quality were carried out for stainless steel tube, Al-alloy tube and copper tube [18,74]. The mandrel design method was proposed.

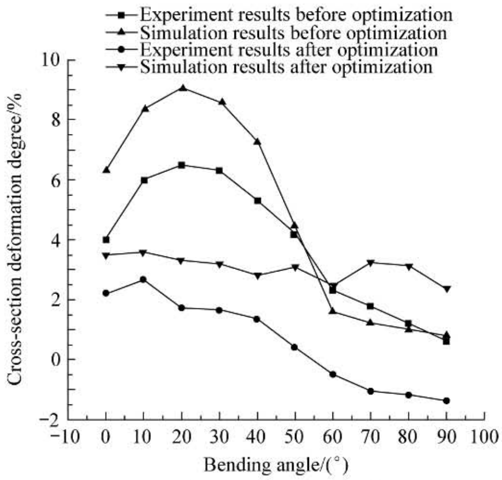
With the development of the computer technology and improvement of the computational algorithms, the pre-design and selection of the process/tooling using the FE simulation have been proved to be efficient and a promising approach. A database management system TUBE has been developed with the pre-forming module integrating data management with FE simulation [75]. The design and optimization method of the mandrel parameters was proposed based on FE simulation for Al-alloy tube bending ( as shown in Fig. 6) [76].The robust tooling/process optimization design should be further developed by using FE simulation, empirical data and analytical formulae.

## 3. Advances on Process/tooling Research

In recent years, there are increasing applications of new lightweight and high-performance tubular bent components as well as the diverse demands in bending specifications in aviation, aerospace and automotive fields. Thus, some innovative tube bending techniques as well as tooling design were developed from the traditional ones to respond to the urgent requirements for realizing efficient, precise, flexible and labor-saving tube bending.




(a) Wall thinning




(b) Cross-section deformation

Fig. 6 Comparison results of Ø 50 mm×1 mm×75 mm (before optimization: $p = 23$ mm, $k = 20$ mm, $r_m =$ 23.85 mm, $r_{nose}= 5$ mm; after optimization: $p = 21.5$ mm, $k = 18$ mm, $r_m = 23.85$ mm, $r_{nose}=2$ mm) [76].

The trends of designing profile structures in traffic systems for space saving, car body safety, lightweight construction and low costs require the manufacturing of complex bent profiles from high-strength steels with high accuracy in small batch production. A new roll-based torque superposed spatial (TSS) bending for three-dimensional tube profiles was developed, leading to higher flexibility and cost efficiency, especially in small batch production (shown in Fig. 7) [77]. By kinematic adjustment of the bending contour and superposing a torque, the variation of the bending radius and bending angle can be implemented. The TSS can be used to reduce the springback and cross-section deformation, while the process is suitable for the forming manufacturing of the bending tubes with relative large bending radius and small diameter.

As to the pushing bending, the forming capability has upgraded from the cold bending of stainless steel tubes to the hot push bending of the large diameter stainless steel tube and Ti-alloy tube (shown in Fig. 8) [78-79]. By combining the expanding with the bending deformation, the oxhorn pushing bending can be used to form the thin-walled ring pipe with even wall thickness [79]. This approach is suitable for the bending forming of the bent tube with small wall thickness. However, it is difficult to obtain the spatial ensemble bent tubes with straight portion in large batch since all tubular should be pushed through the bending die; meanwhile, the wrinkling instability is so prone to occur due to the axial compressive stress induced by the pushing force with inappropriate dimensions of dies.

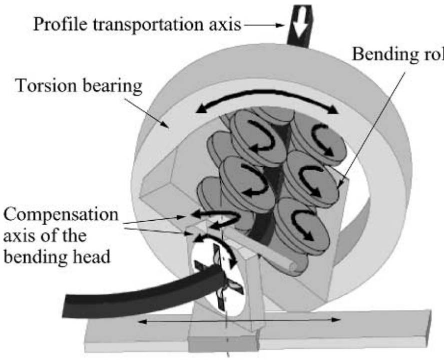



Fig. 7 Principle of flexible TSS bending [77].

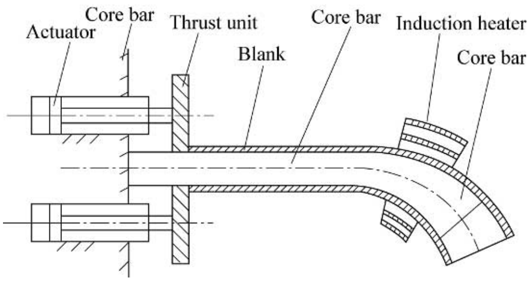



Fig. 8 Tube pushing bending with internal pressure and induction heating [79] .

In the laser bending of tubes (shown in Fig. 9), a continuous laser spot is scanned on the tube surface, and then internal non-uniform thermal stress is induced to achieve the bending deformation [80-82]. This approach has advantages of contactless flexible forming, short production circle and minor springback. Since the overall bending deformation is accomplished by multiple scanning accumulations, the difficult-to-form materials can be bent. However, the limitation exists for continuous batch bending forming of the thin-walled tubes with small bending radius.

The shear tube bending is proposed to realize considerable small bending radii, in which the shear deformation is induced to bend the tubes (shown in Fig. 10) [83]. Based on the traditional press bending, the internal pressure is applied to the bending tube to prevent wrinkling and cross-section deformation, thus improving the bending limit with small bending radii (shown in Fig. 11) [84].

Fig. 9 Laser bending of large-diameter thin-walled tube [80] .

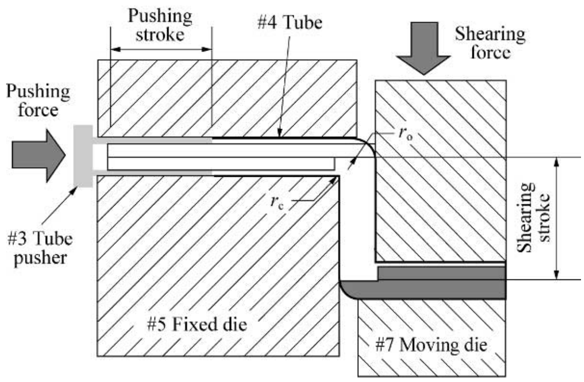



Fig. 10 Schematic illustration of shear bending [83].

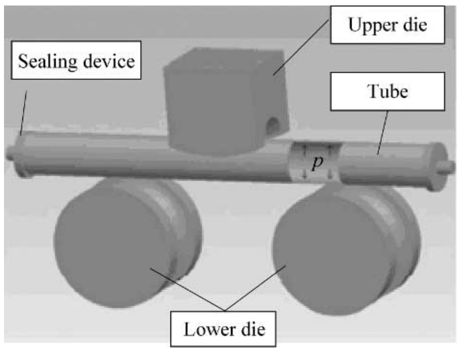



Fig. 11 Press bending of tube with internal pressure [84] .

By integrating the traditional rotary draw bending with NC techniques, NC tube bending has been one of the advanced plastic processing technologies to form thin-walled lightweight tube components in aviation, aerospace and automobile industries (shown in Fig. 12). Under multiple tooling constraints, by strictly controlling the processing parameters, the complex spatial bent components with small bending radii can be achieved more accurately. Thus this process has characteristics of quick batch production capability, high efficiency, cost-saving and stable quality. As stated in Section 2, many studies have been conducted for various tubular materials and bending requirements such as stainless steel tube, high strength steel, high temperature alloy, aluminum alloy and magnesium alloy tube with different shapes and specifications such as round tubes and rectangular tubes. Several companies such as Eaton, Unison and BLM have developed fully electronic servo drive control bending machine, replacing the existing hydraulic drive, to ensure the precise control of the multiple tooling movements.

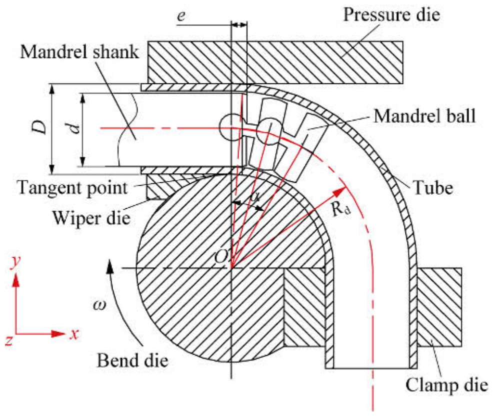



Fig. 12 Schematic diagram of CNC rotary draw bending [18].

## 4. Trends and Challenges of Tube Bending

In response to the urgent needs for accurate and efficient manufacturing of high-performance and lightweight bent tube components in aviation, aerospace and automotive industries, the tends in tube bending theories and technologies arise as below:

1) To further improve the performance of bending tube, new advanced materials gradually concentrate on tube bending applications. Thus the bending technology for each tubular material has attracted more focus currently. It is known that the tubular materials largely determine different tooling setup, forming parameters and forming limit and bending quality. Compared with the stainless steel and aluminum alloy tube, these newly concentrated materials have unique bending characteristics and include magnesium alloy tube, titanium alloy tube, (ultra) high strength tube [85-87], high strength aluminum alloy tube and double-walled metallic tube (laminated tube) [88-89] (shown in Fig. 13).

2) As to the tubular product design, to further realize the function efficiency, the more complex three-dimensional spatial tubular bent components are needed. These bent parts are characterized with large diameter ($D$ >40 mm), thin wall thickness ($t$ < 1.5 mm) and small bending radii (relative bending radii $D/t$ <2). These requirements challenge the development of the precision and efficient tube bending technologies [22,90].

3) New bending processing methods or improvement in machine/tooling design should be developed to satisfy the current requirements for tube bending forming with higher efficiency, more flexibility and more labor-saving. It is noted that the NC tube bending has become the primary technology for realizing the accurate and efficient tube bending [77,83,91] (shown in Fig. 14).

Regarding the above trends in tube bending, the challenges needed to be urgently solved are summarized as below:

1) The efficient and precise tube bending depends on the knowledge about the mechanical properties of the tubular materials, also the reliable FE modeling and simulation rely critically on the sound understanding and the accurate modeling of the unique material response of each tubular material under bending loading. While, up to now, most of the tube properties are obtained still by uniaxial tension tests or directly from the ones of the sheet metal. The ring specimen can be used to estimate the mechanical properties along the hoop direction of tube (shown in Fig. 15) [92], however, the friction effect cannot be avoided and the properties cannot be calculated directly. While, it is known that the tubular materials are generally fabricated with complex processing history and possess remarkable nonlinear and anisotropic responses. There is still a lack of suitable physical tests and modeling theory for tubular materials.

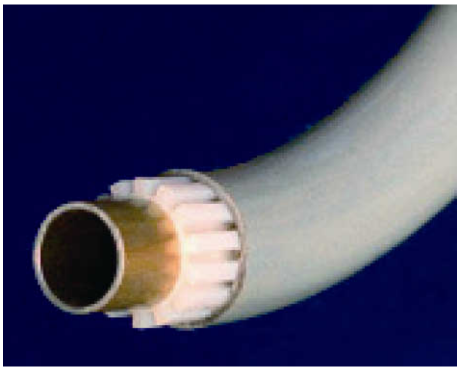


Fig. 13 Double wall bent tube for shrouded fuel lines [89].

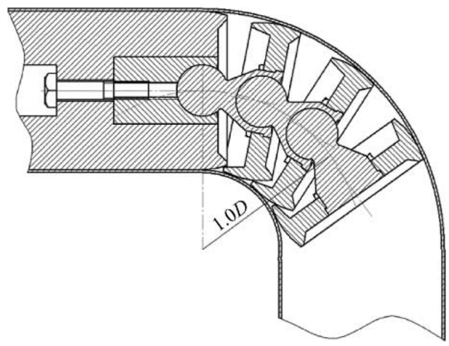



Fig. 14 Flexible mandrel for tube bending with small bending radii [91].

2) Though the multiple defects in tube bending have been studied extensively for various bending processes, the accurate prediction and efficient control of the defects/failures in thin-walled tube bending under multiple die constraints are still scabrous tasks. Especially for large-diameter tube bending with small bending radii, the wrinkling is hard to be avoided or reduced; for bending of high-strength tubular materials,

the springback is affected by so many factors that it is difficult to be efficiently compensated due to obvious fluctuations of the springback. The forming limit under multiple failures/defects should be deeply addressed since there may be various instabilities occurring in tough tube bending deformation.

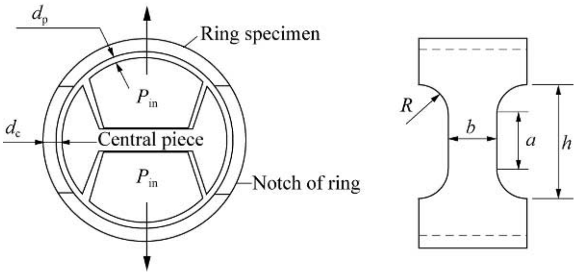



Fig. 15 Ring specimen and tooling setup [92] .

3) The optimization of the overall bending process is still under question. The current study of the process selection mainly focuses on certain tubular materials with certain specifications. Though the FE simulation has been employed widely in product/process design, the "trial and error" routine of the FE virtual computations is still the major methods. In practice, the tooling design is mainly dependent on the professional experiences of the technicians. To efficiently select the process/tooling parameters, the optimization methodology considering the coupling effects of multiple parameters and various defects/failures should be studied. The efficient mathematical models with the multiobjective and multi-constraint should be developed.

## 5. Conclusions

1) Tube bending has been one key manufacturing technology for lightweight and high-strength components in many high-end industries. The current urgent demands for high efficiency and precision production are vitally related to the accurate prediction and effective controlling of the various failures or instabilities in tube bending. This depends on the insight into the occurring mechanisms and influences rules of different defects or instabilities. Thus, advances on the studies of these common topics in tube bending are summarized including wrinkling instability, wall thinning (cracking), springback phenomenon, cross-section deformation and process/tooling design/optimization.

2) With the increasing needs for better performance, the more complex three-dimensional spatial tubular bent components with more lightweight materials are required. These components are characterized with the thin wall thickness, large diameter, small bending radius, and the tubular materials are generally hard-to-deform ones with limited ductility and high strength. Considering the facts of tough tolerance in applications and multiple constraints with nonlinear contact conditions in bending, several challenges should be overcome, viz., the calibration and modeling of the tubular materials, the accurate prediction and control of the multiple defects or instabilities, and the robust optimization of tooling/processing parameters with multi-objective and multiple constraints.

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