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Tube spinning process: Recent advances and challenges

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Abstract: The tube spinning process has attracted much attention because of its simple tooling and good surface finish. This review presents a comprehensive survey of the tube spinning process with a focus on different tube blank materials and spinning methods. The review aims to elaborate the research status of tube spinning process from the aspects of tube material, spinning method and processing performance, and act as a guide for researchers working on tube production and spinning process. In addition, the spinning process will produce large plastic deformation, which will lead to the change of the microstructure of the tube and change its mechanical properties. Therefore, the relationship between the mechanical properties of the tube blank and the spinning parameters is comprehensively expounded from the aspects of yield strength, elongation and material microstructure, and the element diffusion and interface bonding mechanism in the spinning process of the composite tubes are emphatically introduced. In particular, the latest development and trend of composite materials and composite spinning process in tube blank spinning process are discussed. The challenges and prospects of the development of the tube spinning process are put forward, and the direction for future research is pointed out.

Keywords: Tube blank; Spinning process; Materials; Spinning methods; Mechanical properties

1. Introduction

Amidst the sustainable evolution of the economy and society, the issues of energy scarcity and environmental degradation have gained increasing prominence, making energy conservation and emission reduction the focal point of societal concern. Within this context, metal pipe fittings, as essential components, wield significant and extensive influence in domains such as aviation, aerospace, and new energy vehicles. Notably, the burgeoning prominence of advanced plastic forming methods, epitomized by the flexible medium forming process of tubes, has garnered escalating attention[1].

Spinning process, a near-net forming process for blanks, embodies numerous distinctive advantages. Notably, it entails lower forming load, heightened forming accuracy, necessitates only rudimentary tooling, and yields commendable surface finish. Hence, spinning finds wide-ranging application in the fabrication of hollow rotary components, as depicted in Fig.1 and Fig.2[2,3,4,5].

During the tube spinning process, a roller encircles the tube blank on the rotating mandrel, as illustrated in Fig.2, applying spinning force to the tube blank surface to induce axial metal flow and reduce wall thickness. Owing to its localized plastic deformation, in comparison to other plastic forming processes like forging and extrusion, spinning process significantly diminishes the requisite forming force. Moreover, owing to its high production efficiency and minimal material and energy consumption, tube spinning process has found widespread application across automotive, aviation, aerospace, weaponry, and other industries[6]. In a seminal work dating back to 1972, Rammohan and Mishra[1] comprehensively elucidated the mechanical behavior of tubes during spinning and conducted spinning experiments involving industrial pure copper, pure aluminum, and pure lead tube blanks. The findings revealed material accumulation at the rear end of the roller, a phenomenon that may be mitigated through the addition of lubricating oil, warranting further investigation.

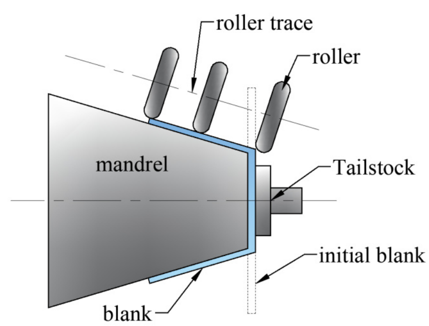

Fig. 1 Slab blank spinning process.

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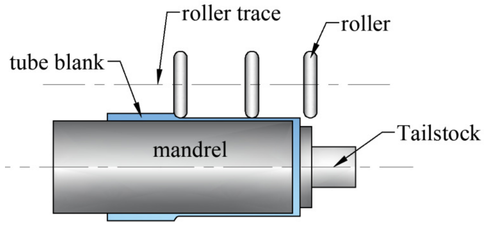

Fig. 2 Tube blank spinning process.

As science and technology advance, an expanding array of materials such as magnesium alloy, aluminum alloy, titanium alloy, superalloy, and composite materials find application in tube spinning. In tandem, in order to meet the technical requirements of the tube, a variety of forming methods based on the spinning process have been developed.

During the metal spinning deformation process, the material undergoes significant plastic deformation due to the repeated rolling of the spinning rollers, leading to alterations in its microstructure1. This effect is particularly pronounced in hot spinning processes and can impact the material's mechanical properties. Excessive deformation increases the likelihood of defects such as wrinkling and cracking occurring[2].

Therefore, this review initially consolidates the utilization of various materials in tube spinning process and elucidates their application scenarios. Subsequently, it delves into the application of distinct spinning methods in tube blank spinning process, the mechanical properties of tube blanks formed by different spinning process and the prediction and control of forming defects are described. Ultimately, it prognosticates the future development directions of tube spinning process.

2. Application of different materials in tube spinning

In response to the burgeoning field of materials science and the diverse demands of various application scenarios, more and more materials are used in tube blanks. Because the spinning process can form the tube blank by hot forming, various difficult-to-form metals, including ferrous metals, magnesium alloys, and titanium alloys, are used in the field of tube blanks. In addition, bimetallic and metal-nonmetallic composite tube blanks are also formed by spinning process[7].

2.1. Ferrous metal tube blank in spinning process

Ferrous metal denotes iron and its alloys, encompassing steel, cast iron, and alloy iron, primarily employed in the machinery, maritime, petrochemical, and metallurgical domains.

Hamed et al.[8] and colleagues investigated the spinning process of 42CrMo steel tubes, scrutinizing the strain distribution across distinct thickness layers and axial positions. Their study expounded on the deformation mode and provided a comprehensive portrayal of the plastic deformation in 42CrMo steel tubes, accounting for strain variation in the thickness direction.

Except for high strength steel such as 42CrMo, stainless steel and other alloys are also widely used in tube spinning process. Takahashi et al.[9] explored the impact of neck length on crack occurrence in the spinning process of SUS409 tubes through experimental and three-dimensional finite element simulations. They calculated the damage value in the simulation results using the ductile fracture criterion equation, investigating the conditions conducive to crack formation and discussing the spinning limit parameters. Furthermore, materials such as T25010,[10] 1Cr18Ni911,[11] 34CrMo412,[12] and AISI-30413[13] are also prevalent in the domain of tube spinning process.

The tube parts made of ferrous metals are widely used in the manufacture of structural parts and mechanical parts such as automobile transmission shafts, bicycle frames, steel structure scaffolds, etc. With the development of lightweight, non-ferrous metals such as aluminum alloys and magnesium alloys are also widely used in tube parts.

2.2 Non-ferrous metals in tube spinning

Non-ferrous metals refer to all other metal mate-rials except iron and steel, mainly including Copper, Lead, Tin, Aluminum, Magnesium and Titanium, etc., with excellent electrical, thermal, strength and other physical and mechanical properties, which are mainly used in electrical, aviation, transportation and light industry and other industries[14].

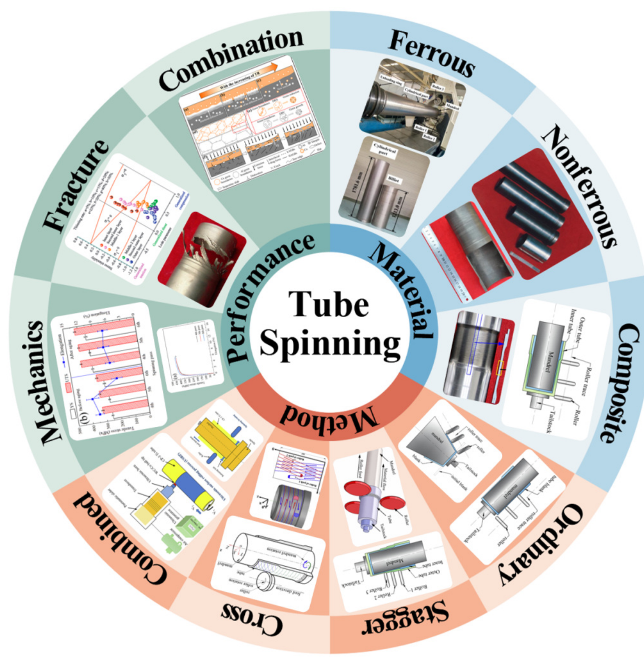

Fig. 3 Research overview of spinning process in tube blank.

2.2.1 Aluminum alloy tube spinning

Aluminum alloy possesses a myriad of benefits, including its lightweight nature, remarkable toughness, ease of processing, and commendable resistance to corrosion. As a fundamental part, it finds widespread application in various modes of transportation such as aircraft, high-speed trains, and automobiles[15,16]. Notably, the 2 series[17], 6 series[18], and 7 series[22] aluminum alloys are extensively employed in the fabrication and shaping of tubes. Among them, the 7 series aluminum alloy, primarily comprised of aluminum, zinc, magnesium, and copper elements, is distinguished by its lightweight properties[19], high specific strength[20] and stiffness, excellent fracture toughness, and superior formability[21]. These attributes underpin the exceptional potential for the application of tubes made from the 7 series aluminum alloy in the realm of lightweight materials. Presently, most of the research on the spinning process of aluminum alloy tubes focuses on the 7 series aluminum alloy tube parts. The research includes the material deformation law and microstructure evolution law during the spinning process.

Zheng et al.[22] conducted the fabrication of 7075 aluminum alloy tubes through power stagger spinning at a temperature of 400 °C, and proceeded to investigate its microstructural evolution and mechanical properties. Additionally, A large number of finite element analysis techniques have also been applied to the analysis of the forming process of the tube spinning. Zhang et al.[23,24] employed finite element analysis to explore the impact of spinning parameters on the elongation of 7075 cast aluminum alloy tubes and scrutinized the temperature field evolution of the 7075 alloy tube during the spinning process. Furthermore, in addition to the spinning temperature, various spinning parameters in the spinning process also have a crucial impact on the forming quality of the tube blank. Molladavoudi and Djavanroodi[25] delved into an examination of the influence of reduction on mechanical properties and macroscopic dimensional accuracy in the spinning process of 7-series alloy tubes.

In addition to 7075 aluminum alloy, a large number of other aluminum alloy materials are also used in the tube spinning process. Therefore, the tube spinning process shows a very high development prospect in the forming and manufacturing of aluminum alloy tube blanks.

2.2.2 Magnesium alloy tube spinning

Magnesium and its alloys, esteemed for their exceptional properties as the lightest metal structural materials, have found widespread application in automotive, aerospace, and other industries. Their high specific strength, specific stiffness, and pronounced damping capacity render them highly desirable[26]. The wrought magnesium alloy AZ31B, renowned for its superior vibration resistance and heat absorption performance, stands as an ideal material for the production of aircraft hubs. Its excellent stability in gasoline, kerosene, and lubricating oil further qualifies it for the manufacturing of engine gear casings, oil pumps, tubing, and various other components[27]. Notably, In the preparation process of AZ31B magnesium alloy tube, spinning process has also become the focus of research. Zhang et al[28]. have contributed to the exploration of the application of AZ31B magnesium alloy tubes in spinning process. Furthermore, AZ91 magnesium alloy tubes have also found widespread utility in the transportation and other pertinent industries[29].

Although magnesium alloy is difficult to form at room temperature due to its own characteristics, because the spinning process can adopt the hot forming method, the deformation resistance of the metal in the forming process is reduced, and the application range of the spinning process is significantly improved. Therefore, the hot spinning process is widely used in the forming and manufacturing of magnesium tubes.

2.2.3 Titanium alloy tube Spinning

The utilization of Titanium alloy thin-walled tube components in the aerospace sector has been extensive, owing to their exceptional mechanical properties such as high strength[30], light weight[31], and high creep strength[32]. The realm of spinning forming for Titanium alloy thin-walled tubes has seen significant advancements in recent years. Notably, Titanium alloy tubes are mostly prepared by hot power spinning process, Gao et al.[33] have enhanced the hot spinning process performance of titanium alloy thin-walled tubes by delving into the study of ductile fracture criteria. Meanwhile, under the hot spinning process, the machinability of titanium alloy tubes has been greatly improved. Therefore, most of the complex shapes or difficult-to-machine tubes are prepared by hot spinning process. Yang et al.[34] has pursued research on Titanium alloy tubes with intricate geometries, successfully devising the spinning process for Ti1300 alloy cylindrical parts with steps. Furthermore, Guo et al.[35] have achieved success in employing rolling-spinning composite forming for the production of Titanium tube.

Beyond the aforementioned metal materials, spinning process has also found wide-ranging applications in copper alloy[36], superalloy[37], NiTiNb memory metal[38], and various other tube types.

2.3 Composite tube spinning

With the in-depth development of industrial technology, the requirements for the comprehensive performance of various metal tubes are getting higher and higher. The composite tube has the characteristics of both substrates and can meet the various performance requirements of the parts at the same time, which promotes the rapid development of composite tube manufacturing technology. Spinning process has the advantages of low load, simple tooling, low cost, good dimensional accuracy, high bonding strength and high material utilization rate, so it is widely used in the preparation of composite tubes.

2.3.1 Metal-nonmetal composite tube

Fiber-reinforced composites, as a category of lightweight materials, have garnered increasing favor in the realm of crashworthiness applications, owing to their superior energy absorption capacity per unit mass when juxtaposed with traditional metal materials[39].

The spinning process is also gradually showing an increasing application prospect in the preparation of metal-nonmetal tubes. Zhu et al.[40] endeavored to fabricate composite tubes by assembling aluminum and CFRP tubes, culminating in the formation of Aluminum/CFRP/Aluminum composite tubes, as depicted in Fig. 4. The energy absorption performance of these composite tubes during quasi-static axial crushing was meticulously examined. Meanwhile, Han et al.[41] achieved the preparation of Aluminum (H-I)/carbon fiber-reinforced polymer (H-II)/ Aluminum composite tube (H-III) with robust interface bonding through spinning process, subsequently scrutinizing its crushing behavior and energy absorption mechanism. A comprehensive analysis of its crashworthiness was also undertaken through a quasi-static crushing test.

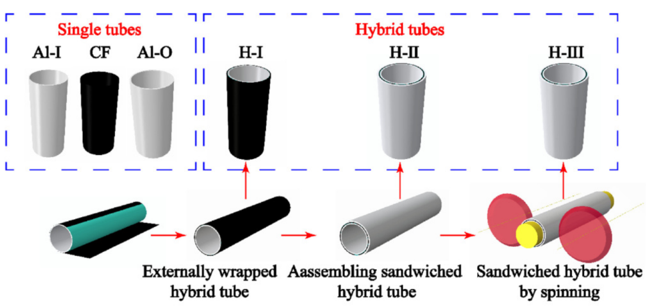

Fig. 4 Aluminum/CFRP/Aluminum hybrid tube [39].

2.3.2 Metal-metal composite tube

Spinning composite process represents a novel method for fabricating double-layer metal tubes, predicated on the spinning process[42]. Metal composite tubes, forged from two or more metals with distinct properties through appropriate processes, surmount the limitations of individual metals and amalgamate the merits of multiple metals. These tubes exhibit high strength, exceptional corrosion resistance, and commendable electrical and thermal conductivity, thereby catering to the requisites of diverse environments. Their application spans across various domains, including oil and gas pipelines, heat exchangers, and aerospace[43].

The spinning process was first applied to the forming and manufacturing of composite tubes of different grades of the same metal. Xu et al.[44] scrutinized the impact of the initial thickness ratio on the bonding strength of 3A21/5A03 composite tubes, crafted through spinning process. In addition to aluminum alloy composite tubes, the spinning process method was also employed to fabricate 20/316L composite tubes[45]. Furthermore, spinning finds extensive utility in the production of composite tubes comprising dissimilar metals. Cheng et al.[46] delved into the application of spinning in Cu/Al composite tubes, while Samandari et al.[42] harnessed spinning process in the shaping and manufacturing of Al-St composite tubes.

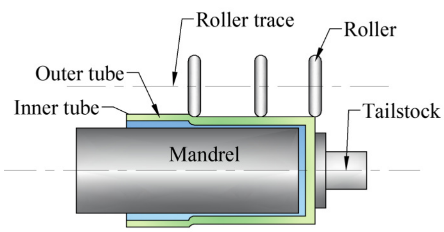

Fig. 5 Spinning process diagram of composite tube.

In conclusion, the evolution of spinning process has facilitated the application of a diverse array of materials in the spinning process of tube components. For ferrous metals, both cold spinning and hot spinning processes are commonly employed in the tube blank forming process. Due to the significant variations in mechanical properties among different grades of Aluminum alloys, various spinning processes have been developed to prepare Aluminum alloy tube blanks. Magnesium alloys, Titanium alloys, and high-temperature alloys are challenging to deform at room temperature, so most of them rely on hot spinning processes. However, with energy conservation and emission reduction becoming a social priority, research into the cold spinning process (Multi-pass ordinary strong spinning) for these metals has also gained increasing attention.

As the operational demands imposed on tube components escalate, scholars have resorted to compounding the tube blanks with disparate inner and outer layers through spinning process, thereby engendering composite tubes inclusive of metal-metal and metal-nonmetal compositions. This approach serves to enhance both the operational capacity and longevity of the tube blanks. Moreover, ongoing research endeavors have engendered the application of increasingly innovative spinning methods in the fabrication of tube components.

3. Different spinning methods in tube forming

In the intricate spinning process of tube components, the configuration of the spinning roller (typically comprising the counter-rollers, three-rollers, and four-rollers, as shown in Fig.6) and the mode of spinning exert a profound influence on the load borne by the spinning roller on the mandrel, consequently exerting a pivotal impact on the quality of tube component formation[47]. Xue et al.[48] have elucidated that the imposition of an uneven load on the mandrel exacerbates its circular runout and eccentricity, thereby detrimentally affecting the tube spinning process and compromising the precision of formation, including the uniformity of wall thickness and roundness of the spun tube fittings.

3.1. Single-roller or multi-roller spinning

The most prevalent method for spinning tube components involves either multi-roller or single-roller single-pass spinning. Owing to the uncomplicated nature of single-roller spinning, most of the research on the tube spinning process focuses on the single spinning roller. For instance, Shan et al.[49] employed the single-roller reverse spinning process to shape a tube and utilized finite element analysis to scrutinize the deformation behavior of the tube during the reverse spinning process. However, as previously highlighted, the unbalanced rotary pressure in single spinning formation gives rise to heightened errors. Therefore, most recent studies have used counter-rollers, three-rollers or even four-rollers to manufacture the required tube parts.

Due to the different distribution of rollers, the spinning process of the tube blank will be affected. Xu et al.[47] developed elastic-plastic finite element models corresponding to diverse spinning roller distribution modes using ABAQUS/Explicit software. They analyzed the impact of these modes on the tube blank spinning process and validated the reliability of their finite element model by comparing it with analytical, experimental, and other finite element analysis outcomes. Additionally, Since the multi-pass spinning process with a single roller can significantly reduce the amount of reduction per pass, the radial load during spinning is reduced and the machining accuracy of the tube is improved. Multi-pass spinning process has also been widely studied. Zheng et al.[50] observed that multi-pass spinning for composite tubes can substantially mitigate wall thickness rebound and enhance the dimensional accuracy of the tube blank.

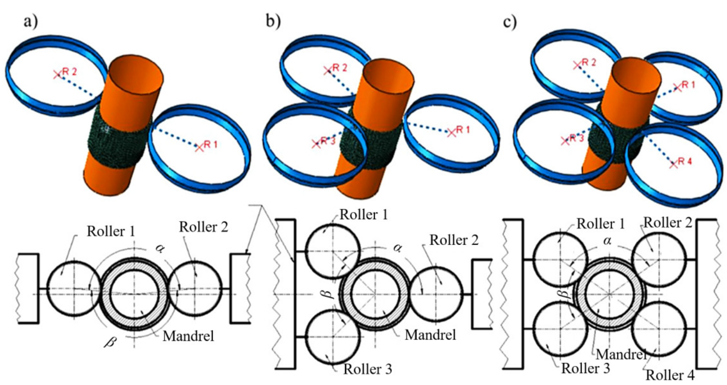

Fig. 6 Counter-roller, three-roller and four-roller spinning process diagram [47].

3.2. Stagger spinning

Stagger spinning process represents a fusion of multi-roller spinning and multi-pass spinning process. By concurrently applying pressure to multiple rollers, errors can be minimized, and tube components can be precisely and efficiently manufactured by regulating the feed rate in a single pass. In comparison with traditional spinning methods, it can enhance the dimensional accuracy of tube parts due to the multiple constraints imposed by staggered rollers. As a result, stagger spinning emerges as a cost-effective and efficient approach for producing axisymmetric parts, particularly for tube components[51].

The stagger spinning process was first applied to the forming of a single tube. Lin et al.[52] constructed a three-dimensional finite element model (FEM) to investigate the impact of stagger spinning parameters on the dimensional accuracy of C-276 cylindrical parts. They observed that the deviation of wall thickness and inner diameter is responsive to the spinning parameters. Based on the findings of the finite element analysis, they derived the optimal stagger spinning process parameters for the studied thin-walled cylindrical parts.

The ability of stagger spinning to augment the overall reduction of the tube by regulating the reduction from different rollers makes it particularly suitable for forming tube blanks with substantial reduction. Zheng et al.[22] successfully fabricated 7075 aluminum alloy tubes with thinning rates of 70% and 85% at 400 °C and room temperature using the potent stagger spinning process. Owing to its capacity to achieve significant reduction while ensuring dimensional accuracy. The large reduction is one of the necessary conditions for the preparation of composite tube, therefore, stagger spinning process is also widely employed in the production of composite tubes. For instance, Shi[53] effectively produced Al/Mg composite tubes utilizing stagger spinning process. Similarly, Yang et al.[43] prepared Al/Cu laminated tubes through power stagger spinning process at room temperature and investigated the inter-. face behavior and mechanical properties of composite tubes with varying thinning rates.

3.3. Cross spinning

In the traditional spinning process, most of the single-roller or multi-roller spinning methods are used to form the required tube blank. In the slab spinning process, the roller trajectory plays a crucial role in the forming quality of the slab. For the tube spinning process, due to its fixed roller trajectory, it seems impossible to improve the forming quality by optimizing the roller trace.

Yang et al.[54] introduced a novel spinning process, referred to as cross spinning, which involves alternately changing the rotation direction of the mandrel at each pass, as depicted in Fig.8. This innovative approach aims to enhance the circumferential strength of the tube. The results indicated that a more homogeneous texture was formed during cross spinning, inducing lower average Schmid factor for prismatic slip system and larger activities of the pyramidal slip systems, was the major cause for enhancing the hoop mechanical properties of the as-spun workpieces compared with that during traditional unidirectional spinning.

3.4. New spinning technology

The traditional spinning process relies solely on the roller and mandrel to apply pressure to the blank for component formation, limiting its ability to control the material's microstructure and stress state. Consequently, achieving high-performance precision forming of components solely through spinning process is challenging. The ultrasonic surface rolling process (USRP) presents a new surface strengthening technology rooted in severe plastic deformation (SPD), integrating ultrasonic impact peening and deep rolling[55]. In the USRP process, SPD is induced by static pressure and dynamic impact, characterized by high frequency and speed, leading to the

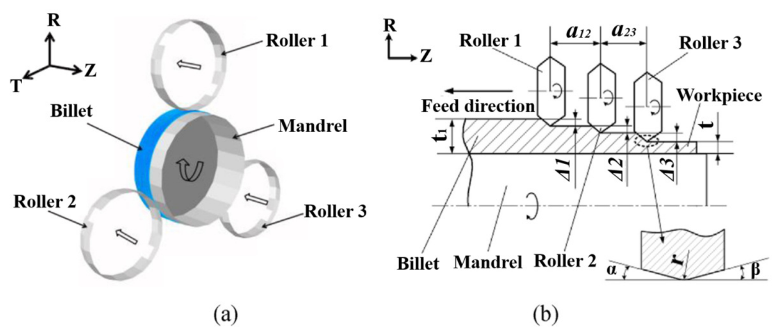

Fig. 7 Stagger spinning schematic diagram[52].

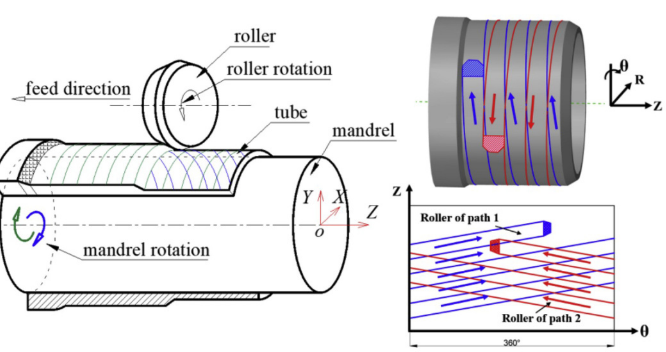

Fig. 8 Cross spinning schematic diagram[54].

formation of a gradient nanostructured surface (GNS) layer.

Compared to other surface treatment methods, USRP offers superior surface mechanical properties and reduced surface roughness. The spinning-ultrasonic surface rolling process (S-USRP) composite forming technology emerges as a promising method for high-performance thin-walled tube manufacturing, as depicted in Fig. 9. This approach not only facilitates the formation of gradient nanostructures on the material's surface but also enhances surface roughness and mechanical properties. Zhang et al. [56] successfully employed S-USRP to form pure titanium thin-walled tubes. Additionally, the mechanism of spinning pre-deformation was elucidated by comparing the microstructure and properties of pure titanium tube, USRP, and S-USRP after spinning.

The various spinning processes mentioned above, such as the multi-pass spinning process, staggered spinning process, interlaced spinning process, and others, are used in different materials and application sites based on their respective advantages and disadvantages (as shown in Table 1). As research on spinning process advances, an increasing array of spinning process methods are being applied to tube blanks' formation, encompassing the aforementioned various spinning methods and unmentioned techniques such as ball spinning[13] and internal spinning. Currently, composite spinning of other forming methods has emerged as a prevailing research trend.

4. Change of material microstructure and mechanical properties during spinning process

4.1. Effect of spinning process parameters on microstructure and properties of tube blanks

The spinning of tube blanks represents an advanced and efficient plastic deformation process for crafting hollow rotary components, constituting a form of near-net forming technology[57]. Furthermore, employing multi-pass strong spinning process induces substantial plastic deformation, resulting in the refinement of the tube's microstructure and enhancement of its mechanical properties[54]. With variations in spinning parameters, the yield strength, elongation, surface hardness, and grain refinement of the tube blank post-spinning exhibit varying degrees of change. Notably, the microstructure fundamentally governs the material's mechanical properties[57]. Hence, the change of material microstructure is the fundamental reason for the change of mechanical properties of tube blank after spinning[58,59].

In the spinning process, many spinning parameters have an impact on the material properties after spinning, such as reduction, feed ratio, roller R angle and spindle speed. Zheng et al.[22] observed pronounced grain refinement in the spinning process experiment of 7075 tube blanks following strong hot spinning. At a reduction rate of 60%-70%, the sample predominantly featured a deformed structure, while at an 85% reduction rate, a recrystallized structure dominated. At 400 °C, as deformation increased from 0% to 70%, the tensile strength and Young's modulus escalated, while elongation decreased due to the combined effect of grain refinement and work hardening (as depicted in Fig.10).

Apart from reduction, other spinning parameters significantly influence the microstructure and properties of the material, encompassing spinning pass, spinning temperature, and feed ratio, among other factors. Nakasato et al.[18] investigated the optimal pass for hot spinning process of 6061 aluminum alloy tube blanks, observing that higher temperatures and fewer passes facilitated easier wall thickness augmentation. This is attributed to the temperature rise diminishing the material's yield stress, leading to localized deformation devoid of work hardening. Meanwhile, an increase in spinning

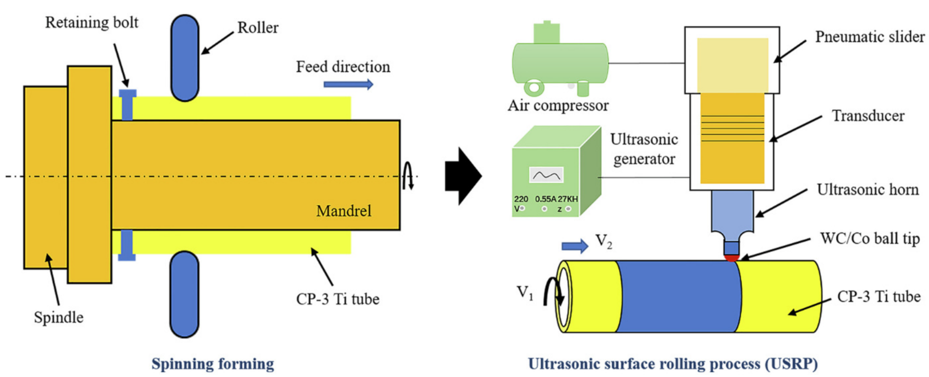

Fig. 9 Ultrasonic surface rolling process schematic diagram[55].

Table 1 Different spinning methods and their advantages and disadvantages.

Spinning methods	Advantages	Disadvantages	References
Single-pass ordinary strong spinning	Strong adaptability, easy tool-assembling	Low forming accuracy	47,48,49
Multi-pass ordinary strong spinning	Low load, low machining error	Long process	50
Stagger spinning	Low load, low machining error, short process	Complex tool-assembling	51,52,53
Ball spinning	Multiple rolling, higher surface quality	Complex die, inconvenient to assembly	13
Cross spinning	High circumferential strength	Complex roller trace	54
Composite spinning	Combining the advantages of other forming methods, greatly improved the overall quality	Many processes, high production costs	55,56

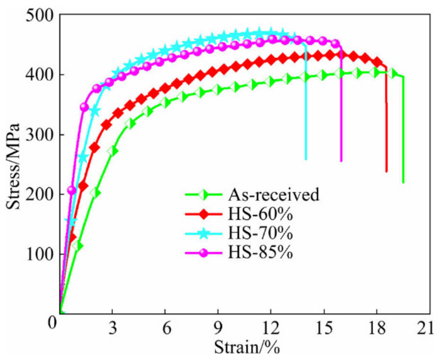

Fig. 10 Mechanical property curves of 7075 tube blank under different reduction rates[22].

passes resulted in augmented flow material and extension in the spinning sample. The optimal spinning conditions for 6061 aluminum alloy were determined as 6 passes at a spinning temperature of 400 °C.

As a kind of light metal with lower density than aluminum alloy, the mechanical properties and damage law of magnesium alloy in spinning forming have also been widely studied. Jin et al.[60] highlighted the narrow optimal spinning temperature window for magnesium alloy tube blanks, ranging from 420 °C to 460 °C. Cracks and over burning were found to occur at lower and higher spinning temperatures, respectively. The tensile yield strength of the sixth spinning magnesium alloy tube, featuring a 1.5mm wall thickness, reached 278 MPa, comparable to that of low-temperature extruded magnesium alloy. Furthermore, the aging effect was noted to further elevate the yield strength of the spun magnesium alloy tube to 352 MPa.

In the process of spinning deformation, if the deformation is too severe, the tube blank is prone to wrinkling, cracking and other defects, the evolution of damage and the ductile fracture mechanism during the tube spinning process have become a focal point for numerous researchers. Hao et al.[61] integrated nine ductile fracture criteria into the finite element software (ABAQUS) to replicate the crack initiation, propagation, and fracture process of TA2 titanium tubes during spinning. These damage models, in conjunction with tensile and upsetting tests, were utilized to anticipate the spinnability of TA2 titanium tubes. The suitability of these criteria was assessed based on the ductile fracture positions of various specimens at the moment of fracture. Building upon this work, Xu et al.[62] incorporated six ductile fracture criteria into the finite element software (ABAQUS) to simulate the damage progression of Ti tubes during spinning. In an effort to elucidate the genesis of surface cracks, the crucial factors influencing damage accumulation, such as equivalent plastic strain, stress state, and principal stress, were scrutinized. Furthermore, the propagation pattern of ductile cracks under varying thinning rates was delineated.

4.2. Effect of spinning process on bonding properties of composite tube

With the advancement of bimetallic tube spinning process, the influence of spinning process parameters on the bonding properties of composite tubes has gradually become the focus of research. Different from the study of single-layer metal tube, the research focus of spinning process of bimetallic tube turns to the diffusion of interface elements and the bonding strength of interface. Mohebbi and Akbarzadeh[63] delved into the spinning process of Cu/Al bimetal composite tubes. The findings revealed that the bonding strength escalates with increasing deformation, particularly when the reduction rate reaches around 30%. However, elevated temperatures result in a decrease in bond strength, attributed to the formation of a brittle intermetallic compound layer at the interface. Conversely, Yang et al.[43] investigated Al/Cu composite tubes through robust stagger spinning process at room temperature. The study encompassed the interface behavior of Al/Cu composite tubes under varying thinning amounts, encompassing the evolution of the interface diffusion layer, microstructural changes near the interface, and the impact of the interface on mechanical properties. The interfacial bonding mechanism during the spinning forming of Al/Cu composite tubes was also scrutinized.

Aside from experimental and simulation analyses, Zhang et al.[64] established an analytical model, providing theoretical guidance for the manufacturing of composite tubes through the spinning process. The model offers the capability to compute vertical stress distribution under different thickness distributions, interface friction coefficients, and yield stress ratios. The results demonstrated that within a specific range, an increase in thinning amount enhances bonding quality. Furthermore, augmenting the friction coefficient of the interface positively impacts the spinning bonding of the composite tube

Chang et al.[46] undertook an analysis and synthesis of the interface evolution, recrystallization mechanism, and fracture mechanism of Al/Cu composite tubes during the spinning process, predicated on the micro-nano interface structure and mechanical properties, as depicted in Fig.13. In essence, the stepped diffusion layer of

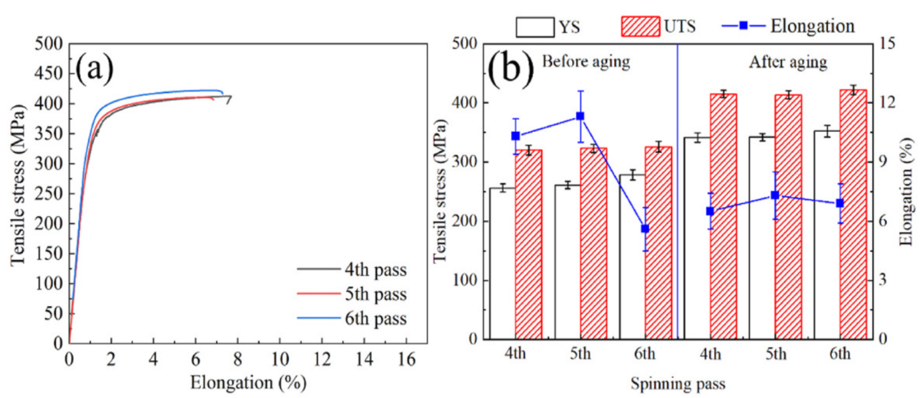

Fig. 11 Mechanical properties curves of magnesium alloy tube under different passes and aging[60].

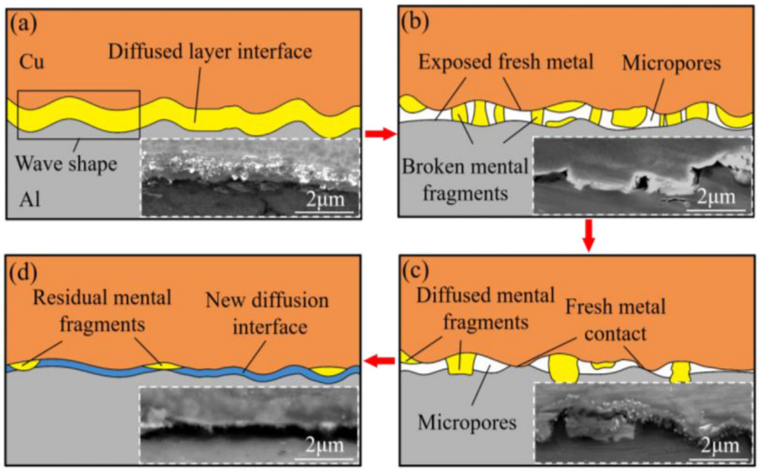

Fig. 12 Interface bonding mechanism of Cu/Al composite tube spinning forming [43].

the interface engenders conditions for stress and strain transfer, following which the diffusion layer ruptures, giving rise to a new interface with an irregular direction under the influence of interface drag force. At this juncture, the deformation of Cu and Al as dissimilar metals becomes discordant, precipitating the deterioration of mechanical properties. Notably, a plethora of dislocations proliferate at the Cu grain boundaries, resulting in grain refinement and nucleation within the original grains, as showcased in Fig. 13 (d) and 13(e). Owing to the influence of DRV, Al grains exhibit growth behavior. Furthermore, distant from the interface, Cu assumes a series of dimples perpendicular to the extrusion direction, while serpentine slip induces lateral sinking of Cu, as evidenced in Fig. 13(f). When the interface drag force succumbs to external forces, dimples and defects manifest at the interface, ultimately leading to the slip deformation of Al along a 45° trajectory away from the interface, consequently causing interface debonding.

Conversely, in the case of a single tube, spinning forming engenders grain refinement within the tube's microstructure, thereby enhancing its mechanical properties. Consequently, the microstructure evolution of tube blank after spinning has become the research focus of single tube. Within the composite tube forming process, the principal performance index influencing the composite tube is the bonding strength. Therefore, the relationship between spinning parameters and interface element diffusion and bonding strength has been widely studied. Moreover, efforts have been made to elucidate and construct the interface evolution, recrystallization mechanism, and fracture mechanism of the Al/Cu composite tube during spinning process, as evidenced in Fig.13.

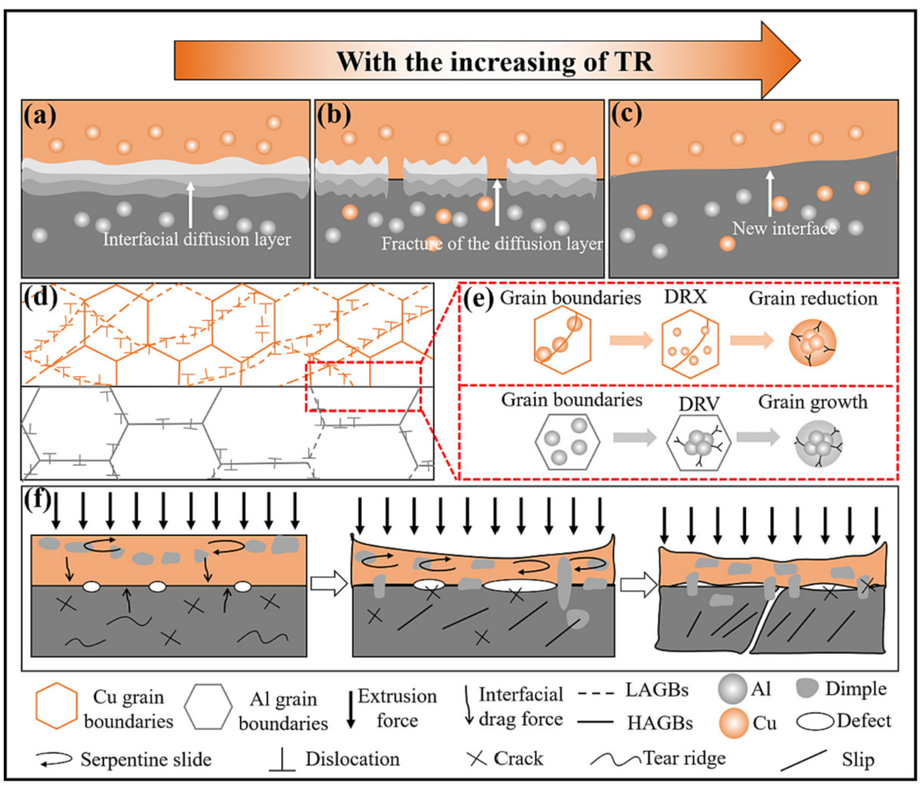

Fig. 13 Interface evolution, recrystallization and fracture mechanism of Al/Cu composite tube during spinning [46].

5. Summary and prospect

This review focus on the utilization of spinning process in tube blank formation. It encompasses an investigation into the application of diverse materials and spinning methods in spinning process, along with a summary of the properties of tube blanks post the spinning process.

Evidently, as spinning process continues to iterate and advance, an increasing number of tube parts are being formed by spinning process, encompassing both ferrous and non-ferrous metals. Concurrently, composite tube components, engineered for more intricate and hazardous environments, are also being fabricated through spinning technology. Moreover, a burgeoning array of spinning methods, including stagger spinning, multi-pass spinning, ball spinning, and internal spinning, are being incorporated in the formation of tube parts. Presently, a burgeoning research trend involves composite spinning, seamlessly amalgamating other forming methods.

For monometallic tubes, substantial scholarly attention has been directed towards the evolution of the structural laws of tube components in spinning process, aiming to discern the mechanical property variations during spinning process. Conversely, in the formation process of composite tubes, owing to the paramount influence of bonding strength on composite tubes, the relationship between spinning parameters and interface element diffusion and bonding strength has been widely studied. Finally, the evolution law and interface bonding mechanism of the composite tube interface of different materials were established.

In summary, the challenges of the tube spinning process in the future are expected to revolve around the research and production of tube components with enhanced accuracy and performance. This includes several aspects:

(1) Heightened focus on the control of roller trace to enhance the surface quality of tube blanks, with particular attention to stagger distance and staggered spinning.

(2) The extension of spinning process to bimetallic and polymetallic tubes, with a particular emphasis on unexplored materials, such as the elucidation of spinning forming mechanisms and interface bonding mechanisms for composite tubes.

(3) The fusion of composite spinning process with other spinning processes, such as spinning-ultrasonic surface rolling composite process and roling-spinning integrated composite forming process. These integrated approaches not only abbreviate the overall process time but also bolster the overall quality of tube blanks, heralding the future developmental trajectory of spinning process.

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