Rare Metal Materials and Engineering
Volume 54, Issue 2, February 2025
Available online at www.rmme.ac.cn

Science Press

Cite this article as: Dong Bowen, Shi Guangyuan, Zhong Sujuan, et al. Research Status of Short Process Forming Techniques for Brazing and Soldering Materials[J]. Rare Metal Materials and Engineering, 2025, 54(02): 377-384. https://doi.org/10.12442/j.issn.1002-185X.20240428.

REVIEW

Research Status of Short Process Forming Techniques for Brazing and Soldering Materials

Dong Bowen[1], Shi Guangyuan[2], Zhong Sujuan[1], Dong Xian[1], Cheng Yafang[1], Long Weimin[1], Zhang Guanxing[1]

[1] State Key Laboratory of Advanced Brazing Filler Metals & Technology, Zhengzhou Research Institute of Mechanical Engineering Co., Ltd, Zhengzhou 450001, China; [2] School of Materials Electronics and Energy Storage, Zhongyuan University of Technology, Zhengzhou 450007, China

Abstract: Short process forming techniques for brazing and soldering materials can shorten the process, improve product quality, and increase production efficiency, which has received much attention from welding researchers. This review mainly summarized the research reports on short process forming techniques for brazing and soldering materials. Firstly, the traditional process and its shortcomings were presented. Secondly, the latest research of short process forming technologies, such as continuous casting technique, atomization powder technique, solder ball forming technique, and rapid solidification technique, was summarized, and the traditional forming performance of several brazing and soldering materials was introduced. Finally, the current restrictions and research trends of short process forming technique for brazing and solder materials were put forward, providing theoretical guidance and reference for related research and technique development in brazing and soldering field.

Key words: short process forming technique; continuous casting; atomization powder; soldering ball; rapid solidification; amorphous filler metals

Nine departments, including Ministry of Science and Technology of the People's Republic of China, National Development and Reform Commission, and Ministry of Industry and Information Technology of the People's Republic of China, jointly issued the *Implementation Plan for Science and Technology to Support Carbon Peaking and Carbon Neutrality* (2022 – 2030) in August, 2022, which clearly requires the solutions optimizing fuel substitution, short process manufacturing, and low-carbon technology to satisfy the green and low-carbon development needs of key industries. Emerging techniques, such as big data, artificial intelligence, and fifth generation mobile communication, should be deeply integrated to lead the zero-carbon and low-carbon reconstruction and digital transformation of high carbon industrial processes. Brazing-soldering technique is an important welding technique, which uses liquid brazing and soldering materials to fill the gaps of solid base materials[1]. Filler metal diffuses with base material and solidifies to form a firm joint. Brazing and soldering technique is widely used in industries, such as aerospace, automotive manufacturing, household appliances, and integrated circuits, which also faces the transformation towards zero-carbon and low-carbon manufacturing.

The components of brazing and soldering materials include almost all metal elements, such as silver, copper, zinc, nickel, manganese, iron, aluminum, and magnesium, and some non-metallic elements (hydrogen, carbon, nitrogen, silicon, and boron) are also included. Most brazing and soldering materials belong to nonferrous metal materials, which are formed by metallurgical and mechanical processing[2–6]. Traditional forming process of brazing and soldering materials has long production duration, and some still suffer from major drawbacks, such as alternating cold and hot processes and repeated energy consumption. In addition, impurities are prone to adhesion to the surface of brazing and soldering material in the long mechanical processing, which affects the

Received date: July 15, 2024
Foundation item: National Key Research and Development Program (2021YFB3401101)
Corresponding author: Long Weimin, Ph. D., Professor, State Key Laboratory of Advanced Brazing Filler Metals & Technology, Zhengzhou Research Institute of Mechanical Engineering Co., Ltd, Zhengzhou 450001, P. R. China, Tel: 0086-371-67710507, E-mail: brazelong@163.com

cleanliness of materials[7–8]. The base material remains at the solid state during brazing and soldering process, and the formation of a strong joint mainly relies on the liquid filler metals[9]. The impurities in filler metals may reduce the fluidity and generate defects, such as pores and inclusions, in the seam and the cleanliness of filler metals directly determines the performance, quality, and reliability of components and major equipment.

Establishing a resource-saving and production intensive circular economy model to manufacture the filler metals through the short process forming technique has become an urgent issue for the development of brazing and soldering industry. This review presents the research reports on the short process forming technique of filler metals, and demonstrates the shortcomings of current research and future development directions, providing valuable theoretical support and reference information for the engineering research and technique development of brazing and soldering materials.

1 Traditional Forming Processes and Shortcomings

1.1 Traditional forming process

Traditional manufacturing process of brazing and soldering materials is shown in Fig. 1[8]. The forming process mainly includes casting, extrusion, rolling, and drawing. Casting is the process of injecting molten liquid alloy into a mold for solidification, forming cylindrical ingots with diameters ranging from 50 mm to 200 mm. Extrusion process uses a hydraulic press (200 – 1000 t) to produce strip or wire: preheated ingots undergo plastic deformation through the extrusion mold. Rolling process is conducted by pulling the strip into a rotating roll and processing by frictional force. The strip undergoes plastic deformation caused by roll compression, resulting in the decrease in cross-section area and the increase in length. Pulling is conducted by pulling the wire out of the hole of drawing die, reducing the cross-section area of wire and increasing the length.

1.2 Shortcomings

The three-flow system flows of traditional forming process for brazing and soldering material are shown in Table 1[8]. Casting and extrusion have a significant impact on the stability of material properties, but they also cause thermal energy loss. Casting process usually contains complex procedures, such as gas absorption, phase transformation, crystallization, exhaust, and impurity removal, which can easily lead to cracks, pits, shrinkage porosity, and voids. Defects, such as extrusion tails, interlayers, microcracks, cracks, grooves, and bubbles, may occur during the extrusion process. Rolling and drawing are cold forming processes, which usually consist of multiple annealing steps, exerting significant impact on the consistency of the material size. The alternative cold and hot processes can also lead to a significant loss of thermal energy. During the rolling process, arching, side bending, waves, and cracking defects may occur; during the drawing process, cracks, peeling, pockmarks, spikes, bamboo joints, stretch marks, and scratches may occur.

Hence, in order to promote energy conservation and emission reduction in the brazing and soldering industry, it is necessary to further analyze and develop the forming process

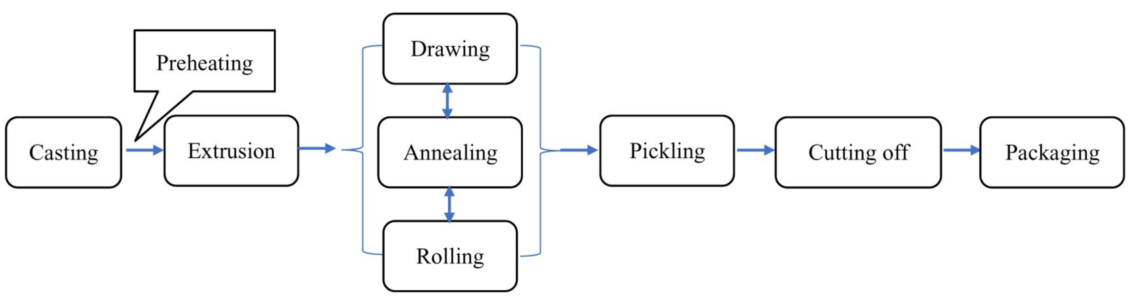

Fig.1 Traditional manufacturing process of brazing and soldering materials[8]

Table 1 Three-flow system flows of traditional forming process for brazing and soldering materials[8]

Forming process	Material flow: Mechanical process	Material flow: Thermal process	Material flow: Chemical process	Energy flow	Information flow
Casting	Fluid gravity	Cooling and solidification	Dissolving and solidifying	Loss of thermal energy and chemical energy	Standard operating procedure
Extrusion	Thermoplastic deformation	Heating and cooling	Recrystallization	Loss of electric energy, thermal energy, chemical energy, and mechanical energygy	
Rolling	Cold plastic deformation	Cycle of heating and cooling	Recrystallization	Loss of mechanical energy, electrical energy, and thermal energy	
Drawing	Cold plastic deformation	Cycle of heating and cooling	Recrystallization	Loss of mechanical energy, electrical energy, and thermal energy	

based on the characteristics of forming techniques for brazing and soldering materials.

2 Short Process Forming Techniques

2.1 Continuous casting

Precision continuous casting technique can produce ultrapure homogenized low-gas-content brazing materials, satisfying the demand for high-performance brazing materials in industries, such as aviation, aerospace, weapons, nuclear energy, ships, and electronics. Lei[10] and Shi[11] et al designed a precision continuous casting equipment, which have advantages of vacuum/atmosphere protection, homogeneous stirring, and high precision. Their continuous casting technique is suitable for the experiments under liquid oxidation condition with severe gas absorption, volatile burning components, high purity requirements, high homogenization, and accurate control of trace elements. Ag-28Cu brazing material, Al-6Mg-0.4Mn-0.2Zr-0.1Ti special aluminum welding wire, and ultrafine ultrapure silicon aluminum wire Al-1.0Si were prepared. The cleanliness and splatter of as-prepared Ag-28Cu brazing material for the electric vacuum devices can satisfy level one requirement, and the comprehensive yield rate increases from <80% to 98% after casting and hot rolling.

Most brazing and soldering alloys are eutectic biphasic alloys or solid solution alloys containing a large number of alloying elements with severe work hardening tendency, so they are difficult to form into strips. Usually, ingots are hot extruded to form flat strips, and then they are rolled and annealed through multiple passes to form thin strips with dimensions of (0.12 – 0.25) mm× (25 – 60) mm. Yu et al[12] designed an upward injection machine with double roll for continuous casting and proposed the thin strip continuous casting technique. According to Ref. [12], the optimal processing parameters should be strip speed of 3 – 8 m/s, thickness of 0.15–0.50 mm, and the width of 4–50 mm. For the $AlSi_{12.6}$ brazing ribbon (0.25 mm×30 mm), the production efficiency is as high as 6 kg/min. The brazing ribbon can be directly cold-rolled, and its dimension changes from 0.30 mm to 0.12 mm with a total deformation ratio of 60%. The prepared brazing ribbon has microcrystalline structure, uniform composition, and excellent performance.

Traditional brittle brazing materials are produced using manual gravity casting process, which has low production efficiency, high labor intensity, high energy consumption, and poor brazing material quality. Zhang et al[13] designed a continuous casting production process for BAl80CuSiNi aluminum-based brazing rods with low melting point and high strength. The casting, cutting, and heat treatment processes for brazing rod production were completed simultaneously on the continuous casting wheel. High frequency mechanical vibration was applied to the newly solidified or partially uncured billet to replace the annealing heat treatment process, achieving the goal of stress elimination, grain refinement, microstructure improvement, and performance enhancement. Meanwhile, the mechanized means was used to achieve continuous casting and fixed length segmentation of the billet, saving energy, protecting environment, and improving production efficiency and yield rate.

Twin roll continuous casting and rolling can significantly improve the production efficiency of brazing materials. Lee et al[14] studied the microstructure and properties of Ag-32wt% Cu brazed alloy prepared by twin roll continuous casting and rolling. The schematic diagram of twin roll strip casting process is shown in Fig. 2[14]. It is found that the twin roll casting and rolling can achieve optimal forming ability and microstructure uniformity. Under the aging condition of 670 °C/2 h, the tensile strength of the strip can reach 283 MPa, and the plasticity significantly improves by 41%. A strip with thickness of 1 mm can be cold-rolled into thin strips with thickness of 80–100 μm.

Ag-28Cu-8Sn (wt%) alloy is a typical medium temperature silver-based brittle brazing material, which is characterized by low vapor pressure, moderate melting point, and high welding joint strength. This alloy has excellent wetting properties for copper, nickel, steel, and Kovar alloys, so it is widely used in the brazing of electric vacuum devices and vacuum chambers. Fang et al[15] prepared brazing wire using continuous casting process and die-free drawing technique, as shown in Fig. 3. The casting microstructure is a typical three-zone structure, including surface fine grain zone, columnar grain zone, and central equiaxed grain zone. The Ag-28Cu-8Sn alloy is composed of face-centered cubic silver alpha phase, complex structured beta phase, and intermediate compounds, such as Ag6.7Sn, Cu0.85Sn0.15, and Cu3Sn. These brittle intermediate compounds result in difficult processing. The die-free drawing process can improve the processing performance

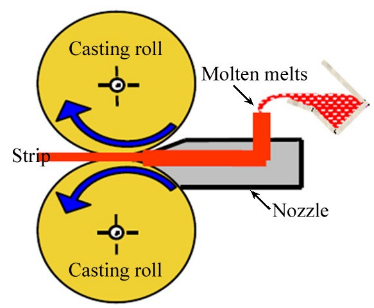

Fig.2 Schematic diagram of twin roll strip casting[14]

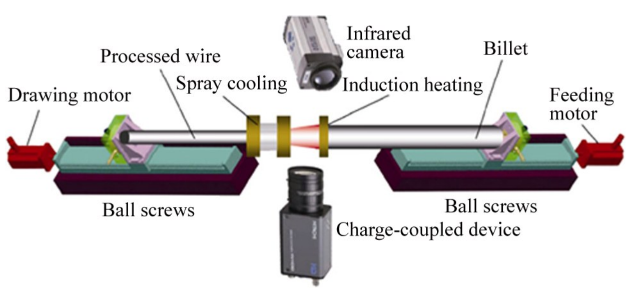

Fig.3 Schematic diagram of continuous die-free drawing process[15]

of Ag-28Cu-8Sn alloy and overcome the defects of severe work hardening, low tensile deformation rate, short mold service life, high wire breakage frequency, and high energy consumption in traditional cold drawing processes. Fang et al[16] also simulated the microstructure evolution of Ag-28Cu-1Ni alloy during continuous casting using 3D-CAFE method, and studied the effects of average nucleation undercooling and distance from the ingot bottom to the cross-section area on the solidification structure. Comparing the solidification simulation results under different process conditions, the optimal process conditions can be determined, as follows: heat transfer coefficient of 2000 W/(m·K)$^{-1}$, pouring temperature of 1113 K, and stretching speed of 1×10^{-2} m/s.

2.2 Atomization powder

During the atomization process, molten metal is subjected to high-speed and high-pressure airflow generated by the atomizing nozzle, which causes the molten metal to form small droplets that undergo spheroidization, cooling, and solidification to obtain the brazing and soldering powder. In order to meet the needs of green composite and high efficiency, the advantages of powder as intelligent brazing and soldering materials attract much attention.

Using atomization technique to prepare brittle brazing powder can solve the difficult processing problem, shorten the process flow, and reduce energy consumption. Yu et al[17] prepared copper phosphorus tin powder using the gas water coupling atomization method and improved the powder sphericity and particle size distribution by adding 0.5wt% silicon. Trace silicon addition can improve the comprehensive performance of copper phosphorus tin powder, whose loose packing density, tap density, and specific surface area increase by 17%, 15%, and 60%, respectively. In addition, the powder particle size reduces from 42.93 μm to 30.88 μm. Du et al[18] used vacuum atomization powder technique to prepare Ni-37Pd-15Cr-1.8B-3.2Si alloy powder, and the obtained powders had spherical and quasi-spherical shapes with particle size <75 μm. Sheng et al[19] prepared BNi-7 high-temperature brazing powder using the atomization method. The prepared BNi-7 brazing powder had good sphericity, normal particle size distribution, low oxygen content (0.019wt%), uniform composition, and good loose packing density.

Pd-containing brazing materials have high melting points, good flowability, and fine wetting properties, which are particularly suitable for high-temperature brazing of nickel-based alloys, tungsten, molybdenum, zirconium, and other metals. Pd-containing brazing materials are widely used in the gas turbines, aircraft engines, missile technology, night vision systems, and nuclear industry. Wang et al[20] studied the preparation of Pd-Ag-Cu alloy powder by inert gas atomization method. With fixed nozzle structure, the variations of superheat, atomization pressure, inner diameter of guide tube, and length of guide tube extension all affect the particle size and yield rate of Pd-Ag-Cu alloy powder. Increasing the superheat and atomization pressure and reducing the inner diameter of the guide tube are beneficial to reduce the powder particle size.

The brazing and soldering powder prepared by ultrasonic atomization method has good sphericity, narrow particle size distribution, and low oxygen content. Xu et al[21] studied the effect of atomization pressure on the microstructure and properties of lead-free soldering powder using ultrasonic atomization method, and the morphologies of powder prepared at different pressures are shown in Fig.4. When the atomization pressure increases from 0.4 MPa to 0.7 MPa, the powder particles are significantly refined, and the atomization efficiency rapidly rises, but the oxygen content slightly increases. When the atomization pressure increases from 0.7 MPa to 0.9 MPa, the atomization efficiency slightly improves, whereas the sphericity and roughness of the powder decrease. When the atomization pressure is 0.7 MPa, high atomization efficiency, uniform particle size distribution, good powder sphericity, and smooth powder surface can be achieved. Sheng et al[22] prepared Al-10Si (wt%) near-eutectic alloys with different Cu, Zn, and Y contents using ultrasonic gas atomization method. The prepared Al-Si-Cu-Zn-Y alloy powder has ultrafine structure, which is not affected by the alloy composition.

The atomizer structure also has an impact on the flow field structure in the vortex zone and the primary fragmentation of the melt. Zhao et al[23] used the commercial fluid dynamics software Fluent to analyze the gas single-phase field generated by four atomizers with different outlet duct angles. In the gas single-phase field of each atomizer, there is a gas vortex region located at the downstream guide pipe, and the gas in the center region flows along the opposite direction.

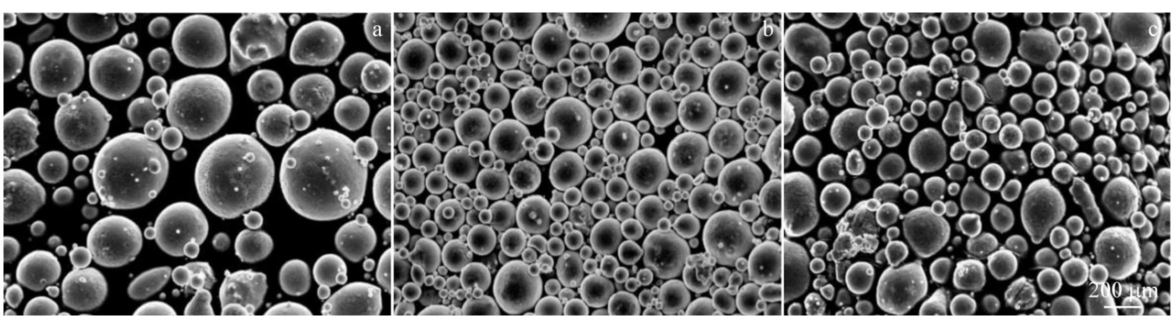

Fig.4 Morphologies of lead-free soldering powder prepared at different atomization pressures[21]: (a) 0.6 MPa; (b) 0.7 MPa; (c) 0.8 MPa

2.3 Solder ball forming

The solder ball forming method is based on uniform droplet spraying technique, which uses piezoelectric pulses to force droplets to spray from small nozzles, therefore achieving rapid preparation and fixed-point printing of droplets with uniform size. This method has multiple advantages, such as uniform droplet size, high yield rate, simple process, low equipment cost, and precise fixed-point deposition. Lv et al[24] used piezoelectric pulse driven uniform droplet spraying technique to prepare lead tin alloy droplets with high dimensional consistency (dimension deviation of ±15 μm), good sphericity, defect-free surface, and uniform dense internal structure. This research provides a new approach for the rapid preparation and maintenance of high-quality solder balls in small batches for high value-added aviation circuit board flip chip solder balls. Wang et al[25] proposed a method to produce uniform solder balls using electromagnetic force and pressure difference control technique, and the schematic diagram of this method is shown in Fig.5. Two pressure difference control methods can be used to prepare uniform Sn-58Bi alloy solder balls. With different diameters and reasonable testing parameters, solder balls with sphericity between 0%−3% and average diameter variation of 4% were prepared.

The droplet deposition manufacturing technique can be used to prepare solder bumps for flip chip bonding, direct solder circuit pins, and fast printing of microcircuits or small components. It has great potential for applications in semiconductor packaging, microelectromechanical system manufacturing, electronics, and display industries. Dong et al[26] studied the relationship between key parameters, stability, and size of SAC305 droplet spray using Pulse Atomization Spray equipment, and the schematic diagram of solidification process and microstructure change is shown in Fig. 6. When the size of solder ball increases, the cooling rate rapidly decreases, resulting in significant differences in dendritic growth inside the solder balls.

In addition to the trace addition of elements, preparing composite solder balls is another method to improve performance of lead-free solder joints. Ko et al[27] prepared Sn-3.5Ag solder balls doped with carbon nanotubes (CNTs) using surface impact mixing technique. When the Sn-3.5Ag solder contains CNTs, the thickness of the intermetallic compound layer between the solder and Ni decreases. Shang et al[28] used SAC305 solder balls as cores and coated them with Sn-Bi low-temperature soldering material, obtaining core-shell SAC305@Sn-Bi composite soldering materials for low-temperature soldering, as shown in Fig.7. The melting point of Sn-Bi eutectic alloy coating is 140.52 °C, and it exhibits good weldability at 150 °C. This research provides a reliable technical path and theoretical guidance for low-temperature soldering, preparation of low-temperature weldable core-shell composite soldering materials, and applications in sensors and optoelectronic devices.

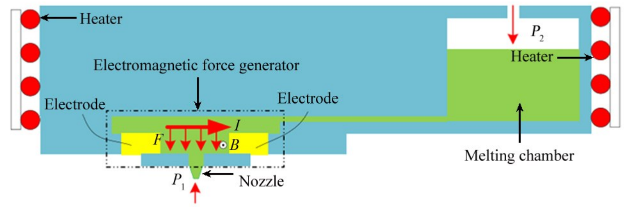

Fig.5 Schematic diagram of preparation of uniform droplets by electromagnetic force and differential pressure control[25]

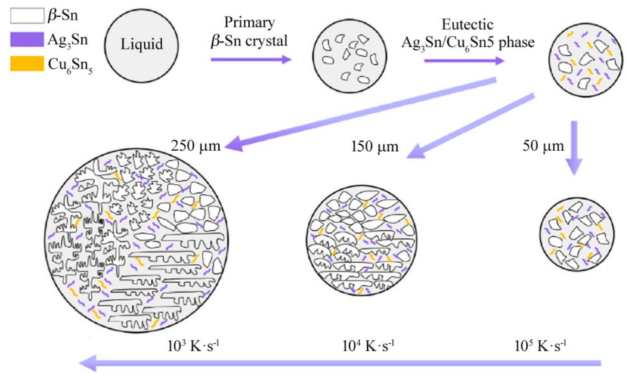

Fig.6 Schematic diagram of solidification process of droplets and microstructure change of solder balls with different sizes[26]

2.4 Rapid solidification

Amorphous filler metals are a new type of material prepared by rapid solidification of liquid metals. The metal atoms do not have time to form an ordered crystal structure phase due to the fast cooling rate[29]. Amorphous filler metals have the advantages of uniform composition, good formability and toughness, low melting point, and good wettability, compared with the crystalline filler metals[30–32].

When the melt undergoes rapid solidification to form

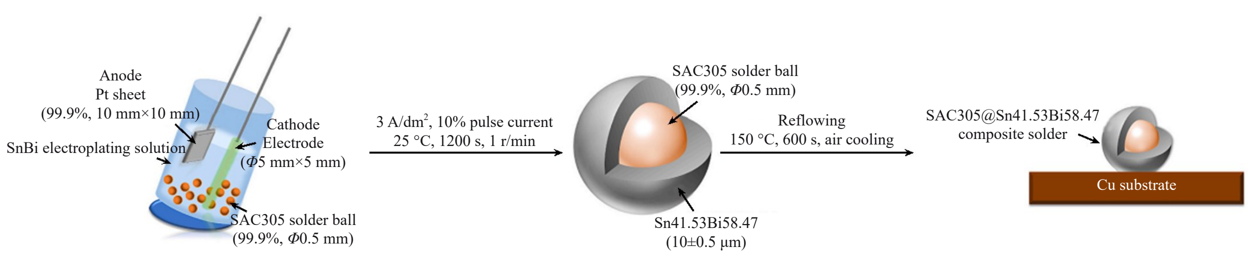

Fig.7 Schematic diagrams of roll plating device, preparation process of core-shell SAC305@Sn-Bi soldering material, and final product with Cu substrate[28]

amorphous material, it is necessary to quickly release a large amount of latent heat, which is normally slowly released during the conventional solidification process. The key to prepare amorphous filler metals by rapid solidification technique is to reduce the volume of melt, to increase the heat transfer rate of the melt thermal medium, and to increase the heat release per unit surface area[33].

Increasing the thermal conductivity rate of the molten heat transfer medium can achieve rapid solidification of brazing and solder alloys. Mold cooling method uses a metal roller or a metal mold with good thermal conductivity for rapid cooling of the melt, ultimately forming thin strips, sheets, or wires. The main methods include single roll melt spinning method[34–39], double roll rapid cooling method[40–41], and metal mold casting method[42–46]. The single roll melting and throwing method is a process where molten metal flows out of nozzle and is sprayed onto the surface of chilled roller, as shown in Fig.8[41]. Then, the liquid film is formed by the high-speed rotating roller and then thrown out under the action of centrifugal force, forming a continuous strip and achieving rapid solidification. The cooling rate can reach 10^6 K/s. Generally, the thickness of amorphous brazing and solder strips is 0.02–0.1 mm and the width is 2–100 mm. The double roll rapid cooling method is to spray molten alloy liquid between two counter rotating rollers, where the molten alloy is subjected to quenching and rolling action of the rollers to form foil strips and to achieve rapid solidification. The double roll rapid cooling method has stronger cooling capacity, can achieve better surface quality, and even produces non-crystalline brazed strips. The metal mold casting method is a process of casting, suction casting, or die casting, where the metal is compressed into a rapid-cooling metal mold and quickly solidifies to form rod amorphous filler metals with diameter of 1–10 mm.

Increasing the heat dissipation surface area of the melt can also achieve amorphous filler metals. The methods to prepare amorphous filler metals include atomization[47–51] and surface deposition[52–56]. Both methods need to atomize the melt into extremely small droplets at the first step, obtaining amorphous powder by rapid cooling. The difference is that the surface deposition method uses the workpiece itself, whereas the atomization method uses a rapidly flowing gas or liquid medium as the cooling medium.

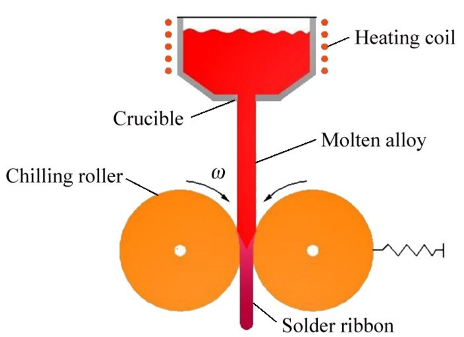

Fig.8 Schematic diagram of amorphous solder material prepared by double roll rapid method[41]

3 Conclusions and Prospect

At present, the most commonly used four short process forming techniques for brazing materials are introduced, but their utilization ratio is less than 10%. The GS107, 5081, CT643, and other spectacle welding wires can be prepared by continuous casting technique, and their yield rates increase by more than 20%, compared with that of the traditional manufacturing methods. In addition, the production cycle shortens by 2 d. Through atomization powder technique, the yield rate of BCuP8 powder improves by more than 10%, and the production cycle shortens by 3 d, compared with those prepared by traditional manufacturing methods. The yield rate of BCu68NiSiB brazing ball prepared by ball forming technique improves by more than 10%, and the production cycle shortens by 3 d, compared with those prepared by traditional manufacturing methods. The yield rate of BTiZrCuNi amorphous foil strip prepared by rapid solidification technique improves by more than 10%, and the production cycle shortens by 4 d, compared with those prepared by traditional manufacturing methods.

Most brazing and soldering materials are multicomponent alloys with large atomic size differences and poor electronegativity between components. They have a randomly packed microstructure, high surface tension, large interfacial energy, and large solid-liquid phase temperature intervals. These factors all affect the flow behavior, heat transfer, and solidification behavior of melts. Although a series of studies on the short process forming techniques of brazing and soldering materials have been conducted, there are still some shortcomings in the current research and applications. Following problems should be focused in the future.

1) Lack of research on near-end continuous casting technique. The size specifications of continuous casting strip or strip brazing materials are relatively large and still require multiple processing steps. The development of continuous casting technique of brazing and soldering materials should focus on the enhancement of casting speed, and the dimension restrictions should also be solved. The continuous casting and rolling as well as continuous casting and drawing should be investigated by not only experiments but also simulation through mathematical models.

2) Obscure mechanism of atomization powder. Although atomization technique is relatively mature, the specific details and property changes of melt deformation during atomization process are still obscure. The influence of melt solidification mode on atomization fragmentation mechanism and the influence of related process parameters and equipment structure on atomization process should be further studied. Through complex numerical models, which contain flow, heat transfer, solidification, multiphase flow, and discrete phase coupling, the atomization and solidification mechanisms can be revealed. Particularly, deep understanding of the nozzle and guide tube structures should be investigated, as well as the influence of related gas and water parameters on the

properties of amorphous powders.

3) Development and investigation of new spherical brazing materials. Most existing balls are solder, whereas brazing materials have complex components. Currently, the spherical brazing materials are rarely reported. Short process forming techniques for spherical brazing materials can refine the grains, uniformize the structure, and suppress the macroscopic and microscopic segregation, obtaining efficient and reliable brazed joints. This development direction has great application potential in aerospace industry.

4) Large scale and industrialization of amorphous filler metals. At present, the development of amorphous filler metals is still in the small-scale trial stage, and how to achieve stable scale and industrialization of amorphous filler metals is a major technical challenge. Digital and automated high-end equipment and intelligent control production processes are considered to manufacture low-cost high-quality amorphous filler metals.

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钎料短流程成型技术研究现状

董博文[1]，史光远[2]，钟素娟[1]，董　显[1]，程亚芳[1]，龙伟民[1]，张冠星[1]
(1. 郑州机械研究所有限公司 新型钎焊材料与技术国家重点实验室，河南 郑州 450001)
(2. 中原工学院 材料电子与储能学院，河南 郑州 450007)

摘　要：短流程成型技术可缩短钎料加工流程、提高产品质量和生产效率，受到焊接工作者的高度关注。本文主要对钎料短流程成型技术的研究报道进行综述。首先，对传统钎料成型过程及存在的不足进行概述；其次，对连续铸造技术、雾化制粉技术、焊球成型技术、快速凝固技术等钎料短流程成型技术的最新研究进行归纳、总结，并介绍了几种钎料的传统成型性能；最后，指出钎料短流程成型技术研究目前存在的不足，同时展望钎料短流程成型技术未来发展方向，为钎焊领域相关研究和技术发展提供理论指导和参考信息。
关键词：短流程成型技术；连铸；雾化制粉；焊球；快速凝固；非晶钎料

作者简介：董博文，男，1990年生，博士生，高级工程师，郑州机械研究所有限公司新型钎焊材料与技术国家重点实验室，河南 郑州 450001，E-mail：dbw1378@163.com