Recent Developments in Vacuum Brazing Furnace Technology

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1. Introduction

Brazing has long since been used as a technique for joining metals—a technique indispensable for our lifestyles. Even in today's manufacturing industry, where many operations are carried out automatically using machines, brazing, both mechanized and automated, continues to be an indispensable technique.

Brazing furnaces, special devices used for brazing, also have a long history. These furnaces are used to manufacture products that require various types of brazing, such as aluminum brazing, copper brazing, and nickel brazing.

In today's manufacturing, where brazing materials are diversifying and products are becoming more and more complex, vacuum brazing furnaces account for a large percentage of brazing furnaces, since these furnaces meet the need to perform brazing without undermining the quality of such materials.

Environmental issues, including the depletion of energy resources, are being hotly debated in recent years, imposing demanding requirements on manufacturing industries. In addition to these environmental issues, manufacturers are also faced with the need to reduce manufacturing costs. Consequently, with a view to covering the needed production with smaller investment amounts, manufacturers often make investments in specialized and large-sized manufacturing devices rather than owning a large number of multi-purpose devices in order to improve production capacity, and to manufacture products in company factories instead of outsourcing their production. For these reasons, investments continue to be made in specialized brazing devices.

Brazing devices include various types of furnaces, such as vacuum brazing furnaces, atmosphere brazing furnaces, multi-chamber furnaces, and single chamber furnaces. In this report, we will focus on vacuum brazing furnaces with multiple chambers, which are suited to the specialized manufacturing of a single type of product and meet the demands of recent manufacturing industries.

2. Vacuum Brazing Technology

A vacuum refers to a pressure lower than the atmospheric pressure. A vacuum brazing furnace is a device designed to braze materials of the same or different types by heating and melting filler metals at vacuum pressures. This brazing technology has various advantages, as shown in Table 1. Among the number of advantages provided by vacuum heat treatment, in this article we will focus only

Table 1 Advantages of the Carrier Gas Method

	Characteristics of vacuum processing	Effects on brazing	Effects
1.	Heating without oxidation	Brazing possible without using fluxes (Anti-oxidation) ・Shortening of manufacturing processes ・Improvement in working environment ・Increase in degree of freedom in product design	・Improvement in product quality ・Cost reduction
		Decrease in wear and tear of product tools	
2.	Vaporization of oil and grease	Possible to remove oil adhering to sample materials No need for cleaning processe	・Improvement in product quality ・Cost reduction
3.	Vaporization of alloy elements	Melt separation of brazing materials ・Brazing defect	Solutions provided by carrier gas method
		Removal of oxide film	・Improvement in product quality
4.	Discharge of solid solution gases	Degassing effects ・Improvement in joint strength ・Improvement in treatment atmosphere	・Improvement in product quality
5.	Radiation heating	Uniform heating of products ・Minimizing heat deformation	・Improvement in product quality ・Increase in yields
6.	Overall heating	Possible to treat products of complex shapes ・Easy to automate processes ・Improvements in working environment	・Improvement in product quality ・Cost reduction

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on those related to brazing. Major advantages include cost reduction and product quality improvement brought about by the shortening of treatment time and the streamlining of the treatment process. However, in order to utilize of these advantages, it is necessary to understand the characteristics of product materials and brazing materials and to maintain appropriate conditions for brazing.

One of the most important points about brazing is the selection of brazing materials. Although pure metals are sometimes used for brazing, most brazing materials are alloys of several different metals. A wide variety of brazing alloys are being developed, from those designed to increase the strength of joints and the corrosion resistance of materials, to those designed to achieve the same joint quality with less expensive materials.

Another important point about brazing is the prevention of melt separation of the brazing materials. The basic cause of melt separation is the difference in melting points of alloy elements. If metals A and B contained in an alloy differ in melting points, metal A, which has a lower melting point, melts first, forming a joint before metal B, which has a higher melting point, starts melting, causing the latter to solidify without forming the joint. This melt separation of materials weakens the joint strength and results in a poorer appearances of products compared with normal brazing.

Vacuum brazing involves other problems as well, such as changes in alloy composition caused by the vaporization of substances with high vapor pressures[2], such as the chromium content of stainless steel. However, it is possible to prevent these changes by using the carrier gas method. While many of ULVAC's vacuum heat treatment furnaces use low vacuum atmospheres, the carrier gas method provides a means of treating metals in an impurity atmosphere equivalent to treatment in a high vacuum atmosphere.

The carrier gas method is a method designed to treat materials by making inert gases flow through a vacuum chamber while evacuating air. Treatment pressures are maintained in most cases between 10 Pa and 1,000 Pa. Figure 1 summarizes the characteristics of the carrier gas method[3].

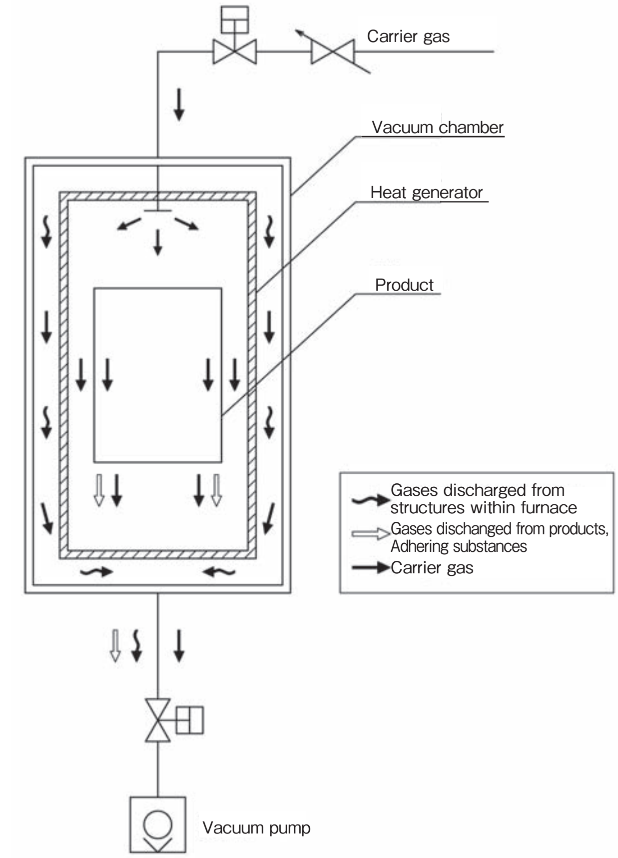

Figure 1 Carrier Gas Method

1) The method makes it possible to create atmospheres equivalent to high vacuums without using high vacuum evacuation pumps.
   Treatment using a gas with a purity of 99.99% at under 100 Pa reduces the absolute pressure of impurities to approximately 1×10^{-2} Pa.
2) Since the method does not use oil diffusion pumps, there is no risk of reflux of diffusion oil, which may contaminate the vacuum chamber.
   The method also simplifies maintenance, reducing costs required for facility investment and management.
3) The method treats materials in a low vacuum, and unlike high vacuum treatment, it prevents the vaporization of alloy elements, thereby reducing changes in the alloy composition and preventing surface roughness in brazed products.
4) The method makes it possible to substitute impurity molecules absorbed into the surface of products and structures within the furnace with carrier gas molecules and remove impurities. It is possible to decrease the concentration of the substances that are substituted and removed when discharging them together with gases.

It is not completely impossible to use the carrier gas method with brazing materials that are purported to be made exclusively for high vacuum treatment, although the method is not necessarily superior to other brazing methods in such cases. It is important to choose an appropriate treatment method based on the shapes and quality of products and the characteristics of brazing materials as well as careful sampling.

We will now explain the treatment processes generally used in brazing. Figure 2 shows a heat treatment process generally used in brazing. There are a number of techniques, such as aluminum brazing and copper brazing, which differ in temperature and other brazing conditions, but the basic concepts are the same. First of all, T1 is the process by which the temperature is raised from the start of heating through temperature t1 to temperature t2. This process removes moisture, oil, and binder components mixed into the brazing material if brazing paste is used. Insufficient treatment during this process may not only cause defects such as the oxidation of brazing materials, but also have negative effects on structures within the furnace. In order to shorten the treatment time, it is necessary to raise the temperature quickly. However, the temperature is sometimes maintained at a certain level for a certain period of time to sufficiently remove binder components.

Process T2 is called the heat balancing process, which ensures uniform temperature distribution across different parts of a product at a temperature lower than the solid phase temperature of brazing materials. Variations in the temperature of a product during brazing cause defects as a result of the melt separation and running of brazing materials. Therefore, it is necessary to maintain the soaking temperature for the minimum period of time required to ensure uniform temperature distribution. T3 is the process by which the temperature is raised from the soaking

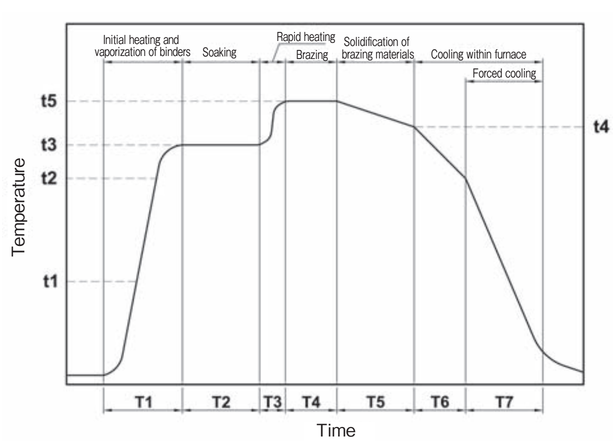

Figure 2　Brazing Processes

temperature to the temperature required for brazing. If the temperature is raised too slowly during this process, it may cause melt separation of the brazing materials. Therefore the temperature needs to be raised at the fastest speed possible.

T4 is the brazing process. The brazing temperature must be maintained for the minimum period of time required to melt the brazing materials and to form the joint. Maintaining the brazing temperature for too long causes the brazing materials to run, resulting in a defective product. Therefore, products must be heated properly and treated for an appropriate period of time so that all brazing materials will melt uniformly.

T5 and subsequent processes are cooling processes. Since forced cooling is not ordinarily performed until brazing materials have solidified, products are allowed to cool gradually in the chamber (in a single chamber furnace) or in the heating chamber (in a multi-chamber furnace) in order to avoid giving a shock to the melted materials. Processes T6 and T7 are cooling processes after the solidification of brazing materials. However, since forced cooling from an extremely high temperature generates thermal stress and causes fractures in products of certain shapes, products are cooled gradually until they reach a given temperature. If they reach a temperature where forced cooling forced cooling no longer cause problems, cooling gases are let into the furnace to cool them until they reach a temperature where exposure to the air does not cause discoloration or oxidation.

3. Characteristics of Vacuum Brazing Furnaces

Treatment with a vacuum brazing furnace requires the processes presented in the preceding section. In order to understand the characteristics of vacuum brazing furnaces, it is necessary to examine not only the heating and cooling processes, but also the evacuation process in detail.

The evacuation process does not involve any serious problems when treating a single batch of products. However, there is a manufacturing quota for each period predetermined at manufacturing sites, and the treatment time is usually set in accordance with this predetermined quota. To treat products within a fixed treatment time, shortening evacuation time becomes of crucial importance. Since antioxidants are not generally used in vacuum brazing, brazing products without properly removing moisture and oxygen from the vacuum chamber atmosphere and products causes oxidation of brazing materials, which in turn may result in defective products. To prevent this, it is necessary to raise the vacuum level sufficiently before heating products and to eliminate moisture before raising the temperature to the level required to remove binder components.

The selection of vacuum pumps assumes great importance for these reasons. A combination of oil-sealed rotary vacuum pumps and mechanical booster pumps is often used for evacuation in recent low vacuum atmosphere brazing furnaces using the carrier gas method, while the same combination plus oil diffusion vacuum pumps are used in furnaces, such as aluminum brazing furnaces, that require high vacuum atmospheres. Even when using carrier gases for treatment, there is a need to reduce the partial pressures of impure gases inside the furnace during the initial evacuation before heating—i.e. to evacuate air until the partial pressures reach levels lower than the treatment pressure with carrier gases. We need to carefully examine the moisture and gases contained in products for treatment, the size of vacuum chambers and the treatment time in order to choose a combination of vacuum pumps that meet the necessary requirements.

As mentioned in the preceding section, brazing quality is affected by the temperature distribution inside products during the heating process. In a vacuum furnace, heat is transmitted by radiation.[5] Although it takes longer for the temperature of the heat generator within the furnace to be transmitted to products by radiation compared with air convection heating, radiation heating has a greater advantage in terms of heat uniformity. Accordingly, vacuum brazing is less likely than other brazing methods to cause fractures and deformations in brazed products, even if no preventive measures are taken. However, radiation heating causes the temperature of the parts of products facing the heat generator to rise more quickly than the temperature of the parts hidden from the generator. Therefore, the treatment time needs to be set by measuring the distribution of temperatures on the surface of products and by examining which parts the temperature rises more slowly in and how long it takes to sufficiently heat these parts.

During the cooling process, in many cases cooling gases are used for forced cooling after brazing materials have solidified to form the joint. However, the important point is not just to cool products quickly, but to choose a cooling process suited to the shape and characteristics of the products. Cooling gases used for brazing include hydrogen, helium, nitrogen, and argon. In terms of cooling performance, hydrogen gas is best suited to brazing, but the use of hydrogen gas requires great caution since it has a risk of explosion. While helium is superior in cooling performance next to hydrogen, it is very expensive and is not suited for practical use in factories. For these reasons, nitrogen gas is used most often as the cooling agent. However, nitrogen gas causes nitridation of some products, such as those containing titan, and in such cases, argon gas is normally used for cooling. Argon, which is inferior to nitrogen in terms of cooling performance and is also more expensive, is seldom used in cases where nitrogen does not cause any such problems.[4]

While vacuum brazing furnaces have the advantages shown in Table 1, they also require careful maintenance. If vacuum pumps are incapable of performing their proper functions in the treatment of products, unnecessary substances may be carried into vacuum chambers, causing negative effects on structures within the chambers where subsequent processes are performed. Air leaks and water leaks also cause coloration of products. If a water leak occurs inside a furnace, it takes at least a whole day to repair the damage and restore the original state. Failures occur in these furnaces just as in other manufacturing machines. In order to avoid failures as much as possible and to maintain the sophisticated vacuum brazing technology, it is necessary to perform checks and maintenance on a

Table 2　Characteristics of Single Chamber Furnaces and Multi-Chamber Furnaces

	Single chamber furnace	Multi-chamber furnace
Characteristic	· Small space for installation · Devices are inexpensive · Simple structure because of lack of conveyor systems	· High productivity · Excels in energy saving performance · Does not cool heating chamber and heat cooling chamber: very efficient · Prolongs useful life of furnace structure

regular basis.

4. Types of Vacuum Brazing Furnaces

Vacuum brazing furnaces are classified by their forms into different types, such as vertical furnaces, horizontal furnaces, single chamber furnaces, and multi-chamber furnaces. Table 2 shows the characteristics of both multi-chamber furnaces and single chamber furnaces. Single chamber furnaces have the advantage that the devices and the space required for their installation are small, since they use a single chamber for all processes from the loading of products, heating, cooling through to unloading. However, since these furnaces are incapable of treating products other than those that have been loaded, they cannot produce a large amount of products per unit time.

Other than the number of chambers, brazing furnaces are also classified in terms of processing pressures. Vacuum furnaces are generally classified into high vacuum furnaces and low vacuum furnaces, depending on whether they use treatment pressures below or above 10^{-2} Pa. Their essential difference lies in the type of evacuation system used: Low vacuum furnaces mainly use a combination of mechanical booster pumps and oil-sealed rotary pumps, while high vacuum furnaces use high vacuum evacuation pumps, such as oil diffusion pumps, in addition to the combination of mechanical booster pumps and oil-sealed rotary pumps.

Figure 3 shows the composition of a typical ULVAC high temperature vacuum brazing furnace with five chambers. It is comprised of a pre-heating chamber, a soaking chamber, a brazing chamber, a cooling chamber and a gas cooling chamber. Atmospheres in different chambers are separated from each other by doors called sluice valves designed to treat products without exposing chambers other than the pre-heating and gas cooling chambers to the air. Unlike single chamber furnaces, this furnace does

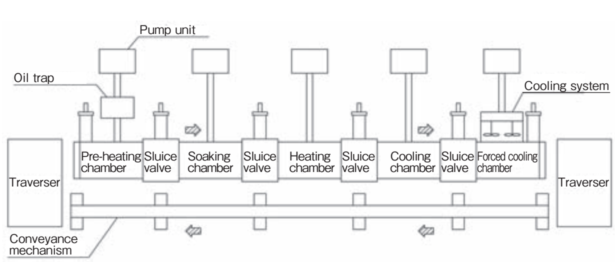

Figure 3 Structure of a Typical High-Temperature Vacuum Brazing Furnace with Five Chambers

not require the heating chamber to be cooled every time products are loaded, thereby improving energy efficiency. With this chamber arrangement, pre-heating (removal of moisture, oil, and binders), soaking, brazing, cooling and forced cooling are performed in separate chambers, so the treatment process that takes the longest time determines the cycle time for loading products into the furnace. This furnace achieves a large increase in production per unit time compared to single chamber furnaces, and so is suited to the mass production of products of the same shape. Since multi-chamber furnaces use separate chambers for different treatment processes, each chamber can be designed to have a structure best suited to its proper treatment process.

A multi-chamber furnace has a conveyance mechanism outside that carries products from the unloading chamber to the loading chamber, which makes it possible to load products directly to and from sample carts.

Thin-type chambers are used for vacuum brazing in both single and multi-chamber furnaces. Thin-type chambers are designed to make it easier for products to receive radiation heat directly from the heat generator and to increase their temperature sensitivity so as to eliminate redundant time required for the raising of temperature. They are also designed to improve brazing quality by enhancing the heat uniformity of products.

As has already been mentioned, brazing quality is affected not only by heat uniformity during brazing, but also by temperature parameters related to heating and cooling. The temperature parameters of products are often measured in order to examine treatment conditions and to track down the causes of defects in brazing. Thus, the measurement of temperature parameters is essential in examining and improving treatment processes. A single chamber furnace designed to enable a thermocouple to be inserted into the furnace wall allows the measurement of temperatures from heating through to cooling. With a multi-chamber furnace, in which products are moved from one chamber to another as treatment proceeds, it is impossible to measure temperatures using a thermocouple inserted through the furnace wall. Accordingly, a memory-type temperature measurement system is required for multi-chamber furnaces. This system is frequently used for vacuum heat treatment furnaces with multiple chambers and is designed to measure and record temperatures by moving within the furnace along with

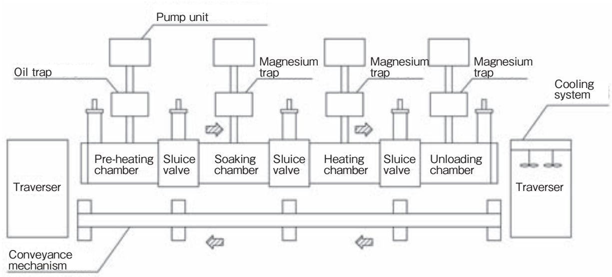

Figure 4　Structure of a Typical Aluminum Vacuum Brazing Furnace with Four Chambers

the products being treated. Many multi-chamber vacuum brazing furnaces are designed to incorporate this system.

Brazing furnaces differ not only in the number of chambers, but also in their structures, which differ depending on the type of products to be treated: i.e. whether they are made of aluminum or copper. In the following sections, we will briefly describe the characteristics of aluminum, copper, and nickel brazing furnaces often used in vacuum brazing.

4.1　Aluminum Vacuum Brazing Furnaces

Figure 4 presents a typical structure for an aluminum vacuum brazing furnace and Figure 5 is a picture of an aluminum vacuum brazing furnace. Since aluminum vacuum brazing is markedly different in brazing conditions from other types of brazing, the structure of the furnace is also different. Therefore, furnaces used for aluminum brazing cannot be substituted for vacuum furnaces used for other types of brazing. The treatment temperature required for aluminum brazing is normally around 600℃ , and brazing is performed in a high vacuum atmosphere, at a level of 10^{-3} Pa, using oil diffusion vacuum pumps. Brazing material contains magnesium[6)] in order to remove the oxides that cause problems in brazing and to prevent oxidation of the brazing material. There are traps in a number of places, including the evacuation pipes, to collect this magnesium in order to prevent it from adhering to furnace walls and flowing into the evacuation system during brazing. However, not all chambers are provided with this mechanism: the pre-heating chamber is equipped with an oil trap system designed to collect cleaning oil removed from products, while the chambers after the soaking chamber where magnesium might spatter all have these magnesium traps. In aluminum brazing, there is no need to decrease the temperature of products down to the room temperature. Therefore, products are removed from the furnace after brazing, with the air in the removing chamber being replaced with outside air.

Figure 5　Aluminum Vacuum Brazing Furnace

If brazing conditions are not satisfied, aluminum brazing is likely to cause product defects due to insufficient melting or running of brazing materials, or excessive growth of alloy layers. Accordingly, aluminum brazing furnaces need periodic maintenance, including the cleaning of magnesium and oil adhering to interior walls.

Aluminum vacuum brazing furnaces have a long history. These furnaces have been used for the manufacturing of heat exchangers for automobiles and electric appliances ever since the aluminum brazing process was invented. Brazing with vacuum furnaces, which does not use fluxes, is an environmentally friendly technology that can also reduce running costs. For these reasons, it has attracted public attention and is used for various purposes. In recent years, however, the Nocolock brazing method, which does not use fluxes or vacuum atmospheres, is used more often than vacuum brazing. Since the Nocolock brazing method does not require vacuum atmospheres, only a limited number of manufacturers are making new investments in vacuum brazing furnaces specializing in aluminum these days. In recent years the use of vacuum brazing furnaces is limited to the manufacture of products that require high levels of purity (ones that are not suited to treatment in the air or cause brazing defects if treated in air), which makes these furnaces all the more irreplaceable.

4.2　Copper Vacuum Brazing Furnaces

Compared with the aluminum brazing furnaces described in the preceding section, vacuum brazing furnaces account for a particularly large percentage of copper brazing furnaces. Copper brazing is used for the manufacture of stainless steel, machine parts made of copper, and heat exchangers.

Copper brazing is normally performed at temperatures between 900℃ and 1050℃ and at pressures between 10^{-2} Pa and 100 Pa. Besides copper alloys, pure copper is used as brazing material. Pure copper has no risk of causing melt separation and has a high wettability with product materials such as stainless steel. Sheet materials and wire materials are also used as brazing materials, along with a method for mixing powdered material with a paste called the binder and applying it to products. Unlike aluminum brazing, copper brazing has no risk of causing magnesium to adhere to interior walls. However, cleaning oil and other substances adhering to products may be degreased by heating inside the furnace and subsequently enter vacuum pumps or remain within the furnace, reducing the evacuation performance or having negative effects on the vacuum level and other conditions of the atmosphere within the furnace. While using vacuum brazing furnaces eliminates the degreasing/cleaning process, a mechanism needs to be created for properly collecting and eliminating grease removed within the furnace. As shown in Figure 3 in Section 3, the pre-heating chamber of this type of brazing furnace has a trap designed to collect grease.

4.3 Nickel Vacuum Brazing Furnaces

Figure 6 shows a photo of a high-temperature vacuum brazing furnace. Nickel brazing is often used for the brazing of stainless steel products. Compared with other brazing materials, nickel brazing material is more resistant to high temperatures and also has a higher resistance to corrosion and oxidation. For these reasons, nickel brazing is widely used for the manufacture of products used at high temperatures, such as gas turbine engines for aircrafts and, more recently, EGR coolers for automobiles.

Nickel brazing is performed most often at high temperatures around 1000℃ to 1200℃ and in vacuum atmospheres between 10^{-2} Pa and 60 Pa. Nickel brazing materials are most often provided in powder form and used mixed with binders. Therefore, binder components that have been heated and removed from products sometimes cause damage to brazing furnaces. What is most likely to be affected is not the interior of heated furnaces, but vacuum pipes and vacuum pumps where binder components adhere, causing a decline in the evacuation performance and a deterioration in vacuum atmospheres. Binder components need to be collected to prevent them from entering evacuation systems.

Figure 6 High-Temperature Vacuum Brazing Furnace

Nickel brazing and copper brazing are classified as high-temperature brazing and use heating mechanisms designed to heat materials to high temperatures, around 1200℃. Since, unlike aluminum brazing, products will oxidate if they are cooled at atmospheric pressures, they need to be allowed or forced to cool in a vacuum atmosphere or gas atmosphere within the furnace until the temperature falls to around 100℃, before taking them out of the furnace. In these respects, nickel and copper brazing furnaces differ greatly from aluminum brazing furnaces.

Powdered brazing materials as well as amorphous foil brazing materials have been developed for nickel brazing. However these materials are expensive, and powdered materials mixed with paste are most often used.

5. Problems with Brazing Furnaces

Due to rises in materials prices in recent years, brazing material manufacturers are developing varieties of brazing materials that are cheaper and have greater, or at least equally dependable, joint strength or corrosion resistance compared with existing materials, causing the variety of brazing materials to increase. As requirements imposed on manufacturing industries become more demanding than ever, manufacturing devices themselves need to satisfy more demanding standards. It is possible to treat products using most of the newly developed brazing materials without making substantive changes to the basic structure of vacuum brazing furnaces, if treatment conditions are properly examined. However, the ease of use and maintenance regardless of the characteristics of brazing materials or products to be treated need to be ensured. In order to meet these requirements, the following problems must be solved.

As new brazing materials are developed and more improvements are made, varieties of binders are also developed to be used by being mixed with metal powder. These new brazing materials are likely to have effects on processes that are not affected by existing treatment methods. Nevertheless, many of the newly developed brazing materials, including binders, are kept confidential as industrial secrets of their manufacturers. Devices like vacuum brazing furnaces are normally operated 24 hours a day, and since it is difficult to maintain furnaces while they are being operated, a mechanism designed to collect binders based on the accurate analysis of their characteristics and to easily remove binder oil thus collected needs to be developed. Research and development are being conducted with regard to this binder-oil trap mechanism, and further improvements will be made in the near future.

Improvements in the performance of devices are required in order to meet the needs to reduce running costs and to save energy. These requirements are becoming more and more demanding, however. In recent years, those engaged in the development of devices are required to make improvements in after-sale services as much as improvements in the functions of separate devices.

Due to the dramatic improvements in the performance of control devices for manufacturing machines, most of these machines are operated automatically, excluding some special operations. There are machines designed to take in program patterns for treating products automatically, with only a few people monitoring them on manufacturing lines. Since production lines are being automated in increasing numbers, the controllability and reliability of machines need to be improved.

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