Brazing Equipment of Diamond Tools

Brazing Overview

Brazing is the most reliable method of joining diamond to metals. It is also the most widely used and one of the areas where processes are held as trade secrets in most companies. This paper attempts to provide a general overview of brazing diamonds, and an overview of recently developed equipment used for the brazing of the components.

Brazing is a method of joining two pieces together using a third, molten filler metal — braze alloy. The joint area is heated above the melting point of the braze alloy but below the melting point of the materials being joined; the molten braze alloy flows into the gap between the other two materials by capillary action and forms a strong bond as it cools. Typically when joining metals, a diffusion bond is created between the two metals to be joined and the braze alloy.

Of all the methods available for metal joining, brazing may be the most versatile. Brazed joints have great tensile strength — the_y are often stronger than the two metals being bonded together. Brazed joints also repel gas and liquid, withstand vibration and shock and are unaffected by normal changes in temperature. Because the metals to be joined are not themselves melted, they are not warped or otherwise distorted and retain their original metallurgical characteristics.

The process is well suited for joining dissimilar metals, which gives the assembly designer more material options. Complex assemblies can be manufactured in stages by using filler metals with progressively lower melting points. Additionally, a braze alloy ma_y be chosen to compensate for the thermal expansion coefficient differences between two materials. Brazing is relatively fast and economical, requires relatively low temperatures and is highly adaptable to automation and lean manufacturing initiatives.

Brazing of diamond to metallic substrates differs significantly from brazing to join metals. Rather than relying on capillary action and a diffusion bond, the brazing of diamonds relies on a chemical reaction.

Factors to Consider When Brazing Diamond

Much has been written in the literature regarding the brazing of diamond. For the purposes of this presentation, we are going to highlight the areas which drive the selection of a brazing method and equipment.

By far the most important factor to consider when brazing diamond is the graphitization of the diamond. Once the diamond has undergone this transformation, it losses its desired mechanical properties. When graphitization occurs is a function of type of diamond, ox_ygen level and temperature.

For example: Single crystal natural diamond starts the graphitization process at 2910° F (1600° C) in a pure inert atmosphere, 2732° F (1500° C) in a vacuum of 5 x 10^{-6} torr (5 x 10^{-4} Pa), 2192° F (1200° C) in a vacuum of 1 x 10^{-4} torr (1 x 10^{-2} Pa), and 1832° F (1000° C) in air at atmospheric conditions.[1]

Graphitization Start of Single Criystal Natural Diamond

Atmosphere		Temperature	
torr	**Pa**	**F**	**C**
760	1×10^5	1832	1000
1×10^{-4}	1×10^{-2}	2192	1200
5×10^{-6}	5×10^{-4}	2732	1500
	Pure Inert	2910	1600

For sintered PCD, graphitization can be enhanced above 1300° F (700° C) when it contains up to 10 volume percent metallic phase. Brazing temperatures for this material are limited to a maximum of 1832° F (1000° C) with slow heating and cooling rates between 1300° F and 1832° F (700° C to 1000° C).[2]

While complete graphitization of the diamond will have detrimental effects on the mechanical properties, it is used in the brazing process. Metals do not diffuse and are not dissolved in the diamond. However diamond does form carbides relatively easily. Researchers have discovered that by adding Ti, Cr, Ta, and/or Si to brazing alloys, stable carbides are formed which wet and allow the brazing of diamond to many materials.[3] These materials are known as active brazing filler metals. Alloy systems including Cu-Ag-Ti, Cu-Sn-Ti, or Ni-Cr-B are common brazing filler metals for joining diamonds to metals, and ceramics.

Some commercial Brazing Filler Metals Used to Join
Diamonds with Metals, Ceramics and cemented Carbides

	Composition	Solidus Temp		Liquidus Temp		Brazing Temp	
Brazing Filler Metal	**Wt%**	**F**	**C**	**F**	**C**	**F**	**C**
Nicrobraze LM	Ni-7Cr-3Fe-4.5Si-3B	1780	970	1832	1000	1850-2140	1010-1170
Metglas MBF-1011*	Pd-40Ni-5Co-4.5Mo-5Si	1556	847	1643	895	1740-1652	900-950
Metglas MBF-15	Ni-13Cr-4.2Fe-4.5Si-2.8B	1769	965	2017	1103	2100-2050	1150-1120
Nicro-B	Ni-15.2Cr-4B	1918	1048	1996	1091	2012-2084	1100-1140
Nicuman 37	Cu-9Ni-23.5Mn	1740	950	1751	955	1760-1832	960-1000
High Temp 095	Cu-9.5Ni-38Mn	1616	880	1697	925	1740-2000	950-1090
Ticusil	Ag-26.7Cu-4.5Ti	1436	780	1652	900	1688-1760	920-960
Incusil-ABA	Ag-27Cu-13In-1Ti	1121	605	1319	715	1345-1400	730-760
Palnicro 36M	Ni-36Pd-10.5Cr-3B- 0.5Si	1508	820	1760	960	1790-1875	975-1024
Palnicro 30	Ni-30Pd-10.5Cr-2.4B	1725	941	1790	977	1825-1900	995-1035
BrazeTec CB10	Ag25.2Cu-10Ti	1436	780	1483	805	1560-1740	850-950
TiBraze 375	Ti37.5Zr-15Cu-10Ni	1516	825	1535	835	1562-1652	850-900
TiBrazeAL-655+	Al-6.3Cu-0.3Mn-0.2Si-0.2Ti-0.2Zr	1010	545	1190	645	1220-1292	660-700
TiBrazeAL-642+	Al-5Si-0.8Fe-0.3Cu-0.2Ti	1115	602	1190	645	1220-1274	660-690

*Brazing of cemented carbide substrates and cemented carbide with diamonds sintered in carbide matrix +Brazing of diamond coated by Mn or Ti film

Sources: Shapiro, A. Brazing Handbook, 2007, American Welding Society, Miami'; Data from Wall Comonoy Corporation, 2005 Product Catalog, Madison Heights, Michigan:Wall Comonoy Corporation; WESGO Metals, 2004, Product Catalog,and 2008 website, Hayward, California: WESGO Metals; Lucas Milhaupt, 2004, Product Catalog, Cudahy, Wisconsin: Lucas Milhaupt; Brazetec, 2005, Product Catalog, South Plainfield, New Jersey: Brazetec; Metglas website, 2008, Metglas Incorporated; Titanium Brazing, Incorporated, 2005, Product Catalog, Columbus, Ohio: Titanium Blazing, Incorporated.

Very careful control of the temperature during the brazing cycle is not only important in effective wetting but also has a direct effect on the strength of the joint. The joint strength is a function of the kinetics of reaction between the braze alloy and the diamond. The two most important factors are the temperature and hold time to facilitate the kinetics. The objective is to achieve the optimal thickness of the carbide layer.

For example: Diamond wafer 0.02 in (0.5 mm) thick and 2 in (50mm) OD was brazed to a cemented carbide substrate in vacuum.[4]

Joint Strength (ksi)	Brazing Temperature Range (F)	Hold Time (min)
17.4 to 18.8	1616 to 1688	20
13.05	>1688	20
7.2	1616 to 1688	3

Based upon the above discussion, it is obvious that the most important attributes needed in a diamond brazing system are temperature and atmosphere control. This was further confirmed by a survey of diamond brazing facilities. These facilities were asked to rank various attributes and to provide a score for each attribute. This allows us to determine relative ranking between the attributes. The results are as follows:

HEATING SYSTEM ATTRIBUTES FOR DIAMOND BRAZING

Attribute	Points
Temperature Variation/Uniformity	30
Atmosphere Control	25
Temperature Control - Ramp up & down	15
Total Cycle Time	5
Whole Part Heating	5
Energy Efficiency	4
Operating Expense	4
Initial Capital Expense	4
Process Documentation - What happened during the cycle	4
Ease of Maintenance	2
Maintenance Costs	2
Total	**100**

The above survey results confirm the necessity for temperature and atmospheric control to limit the graphitization of the diamond. Based upon these results, it is a given that any brazing equipment must have temperature uniformity/control, and atmospheric control. All of the other attributes such as total cycle time, energy efficiency, etc. could be product differentiators between brazing equipment systems.

The interesting result was how low the initial capital expense attribute was when compared to others. This is the one attribute that did surprise us. However, considering the desired results from the equipment as far as the temperature uniformity and atmospheric control one can understand that the one time capital expense would be much lower in scoring. In order to initiate our review of various diamond brazing equipment options, we must first review the braze alloy form, type of atmosphere control, and sources of heat available in the market.

Braze Alloy Form

There are two forms that diamond braze filler metals may come in: 1) paste and 2) foil.

Braze paste has the alloy mixed with binders or suspending agents. This semi-solid material is designed to be dispensable through a syringe or similar device. The advantage of the paste is its ease of application, however there are a couple of downsides to it.

From the economic standpoint, braze paste costs much more per gram of alloy than the solid form. Additionally, it must be heated slowly in a vacuum atmosphere to allow for the binder to evaporate. Heating paste too Quickly (i.e. with direct resistance or induction) will cause the paste to splatter resulting in a poor Quality joint.

Foil (preforms) are solid braze filler metal. This form of alloy costs less per gram, and is independent of the source of heat. However, it may reQuire additional or more sophisticated fixturing than paste.

Atmosphere Control

There are two effective atmospheric control systems that may be used: 1) Inert Atmosphere and 2) High Vacuum.

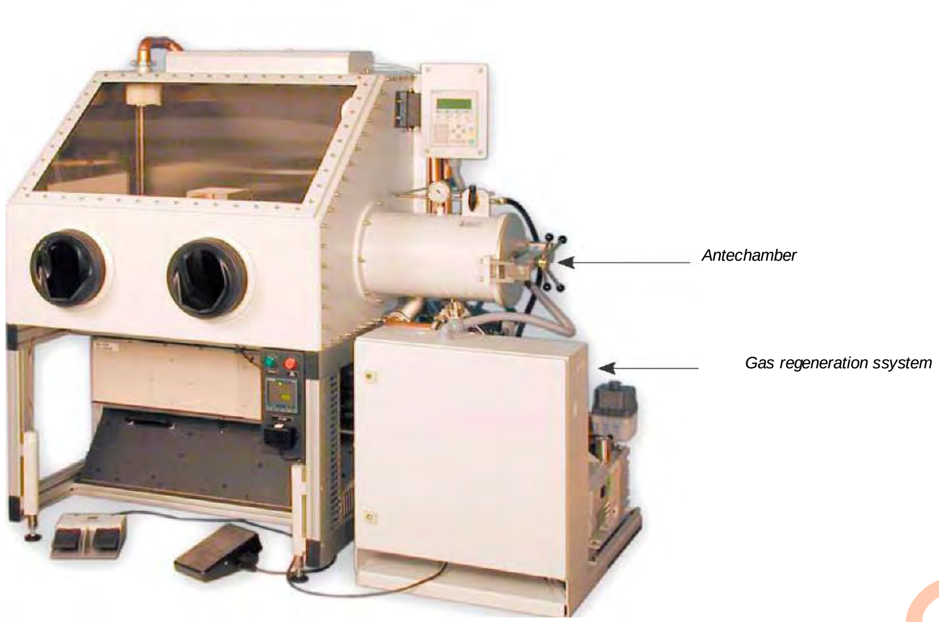
When referred to in brazing applications, an inert atmosphere is one in which there is very little (< 1 ppm) or no oxygen present. Typically the atmosphere is comprised of H, He, N, or Ar or some combination thereof. The general practice for brazing of diamond, is to use an Ar or 95% Ar, 5% H atmosphere. With either of these atmospheres, it is imperative that all of the oxygen be removed.

While there are systems in place in which an Ar cover gas is used during a laser brazing of diamond process, this paper is intended to cover the more prevalent forms of heating and atmospheric control.

The most robust method of ensuring that the majority of the oxygen has been removed is to have a roughing pump system which pumps down, the heating chamber, and then the chamber is backfilled with an inert gas. This process is repeated for a total of 3 to 5 cycles to ensure that an acceptable atmosphere is achieved.

One universal piece of equipment is an inert atmosphere glove box system. These systems have a main chamber which is constantly held at a slight positive pressure of inert gas (Ar or N). A load chamber, also called an antechamber, is located on one side through which the parts are introduced. The antechamber has a roughing pump and follows the above procedure before the parts are introduced into the main chamber.

There are two uniQue aspects of these types of systems. The first is that the system can incorporate integrated oxygen and water vapor monitors which will not allow the heat source to be turned on unless the prescribed atmosphere is achieved. Secondly, the inert gas is constantly cleaned and reused in the system, which keeps operating costs very low. A variety of sources of heat (infrared, resistance, and induction) may be used in these systems. Alternatively, a purge type of system may be used.



Inert Atmosphere Glove Box System

Purge type of systems rely on the relative weight of the inert gas in comparison to air for the removal of the oxygen. For example — argon is heavier than air, so it would be introduced into the bottom of the purge chamber. Since it is heavier, it will want to stay at the bottom of the chamber. As more Ar is added, it forces the lighter air molecules out of the top of the chamber.

For most types of systems, the quality of the inert gas is very important for a successful process. The use of a dew point measurement system will identify if the inert gas is of low quality. These systems may be integrated in, or be a standalone system located within the facility. It is desirable to have a dew point measurement of less than -50° C. In the recirculation glove box systems, the gas regeneration system can actually clean the incoming inert gas.

Generally, the 95% Ar, 5% H atmosphere is used when the heating chamber is not hermetically sealed and oxygen is allowed to leak in. The hydrogen acts as a reducing agent to remove some of the oxygen from the system. Generally speaking, if a system has to rely on the use of hydrogen, then there is a fundamental flaw in the sealing against atmosphere.

If a braze paste is being used, it is highly recommended that an inert atmosphere not be used. As previously discussed, as the braze paste is heated, the binders, which are generally polymeric in nature, are evaporated. If the atmosphere does not remove these polymeric compounds, they may become a constituent in the joint thereby reducing its strength.

High vacuum systems are generally defined as those systems which operate in pressures of 1×10^{-3} to 1×10^{-9} torr (100 mPa to 100 nPa). These systems are generally composed of either a turbo molecular pump backed up by a roughing pump, or an oil diffusion pump backed up by a roughing pump. Since most brazing processes result in outgassing, most high vacuum systems use an oil diffusion pumped system due to the robustness of the pumping scheme. This is especially true if paste is used as the alloy form.

While the initial investment is higher for a high vacuum system, the process robustness is much greater. The overall value of these systems must be evaluated.

Sources of Heat

In general there are 6 different sources of heat used for the typical brazing process: Flame, Furnaces, Infrared, Induction, Dip, and Resistance. For this discussion, we are going to limit our overview to those methods most wildly used in the brazing of diamonds: Infrared, Resistance, Electric Resistance Furnaces, Induction and Induction Furnaces.

Infrared

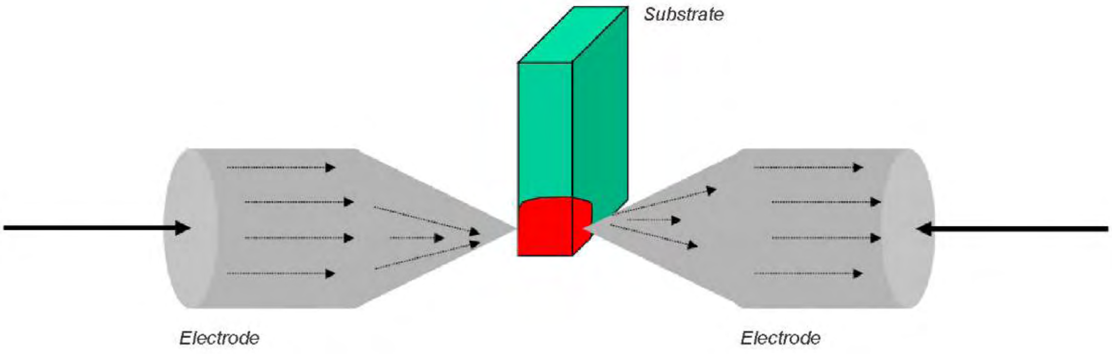
Infrared brazing uses high-intensity Quartz lamps to generate electromagnetic radiation wavelengths greater than the visible spectrum. This radiation is absorbed by the part to be brazed. Infrared brazing was developed for the brazing of honeycomb panels.

Infrared brazing is effective when there is a high surface area-to-mass ratio (i.e. honeycomb panels). While the heat input varies as the sQuare of the distance between the assembly to be brazed and the Quartz lamp, the lamp does not need to follow the contour of the part exactly. Infrared systems rely on thermal conduction to remove heat from hot spots and to carry the heat to those areas not directly exposed to the lamps.[5]

Parts may be placed into a Quartz retort or bell jar which can have a protective atmosphere. The Quartz lamps are arranged outside of the retort or bell jar and the part is thermocoupled for closed loop temperature control. Proper positioning of the thermocouple when using infrared heating is critical to a successful process. This is especially true when trying to braze diamonds onto complex geometries.

While nearly 100% of the energy used by the lamp is converted into electromagnetic radiation, not all of this radiation reaches the part. Radiation is converted into not only infrared, but also visible light. Additionally there are significant losses since the lamps are on the outside of a chamber and the parts are on the inside. Maintenance costs are Quite high since the lamps must be replaced.

High vacuum, infrared system at ORNL



Resistance

Resistance brazing is a process whereby the heat generated in the braze joint is a result of the electrical resistance to an electrical current flow. Heat is generated in either the components to be brazed, the electrodes that contact the components, or both.

Resistance heating is very localized and rapid. It tends to have very poor temperature control with significant differences arising across the braze joint and substrates.[6] Additionally, due to the fact that one piece must be done at a time, it can only be considered for very low volume applications.

Resistance brazing is the most energy efficient, and least costly for capital and maintenance. However, given that it produces significant temperature gradients, and temperature ramp up and down is difficult to control, its use in brazing diamonds is limited to very specific part configurations and very low volumes.

Resistance brazing equipment is very similar to resistance welding equipment. Many resistance welding equipment manufacturers produce systems which may be used for brazing as well as welding.

Resistance brazing equipment. Photo from Asiatic Welders

Electric Resistance Furnaces

A common source of heat for brazing diamonds is radiant heat produced in an electric resistive furnace. Resistance heating relies on a current being passed through a resistive material such as graphite, molybdenum, tantalum, etc. The electrical current is connected directly to the heating element. Heat from the element is then radiated towards the part to be heated.

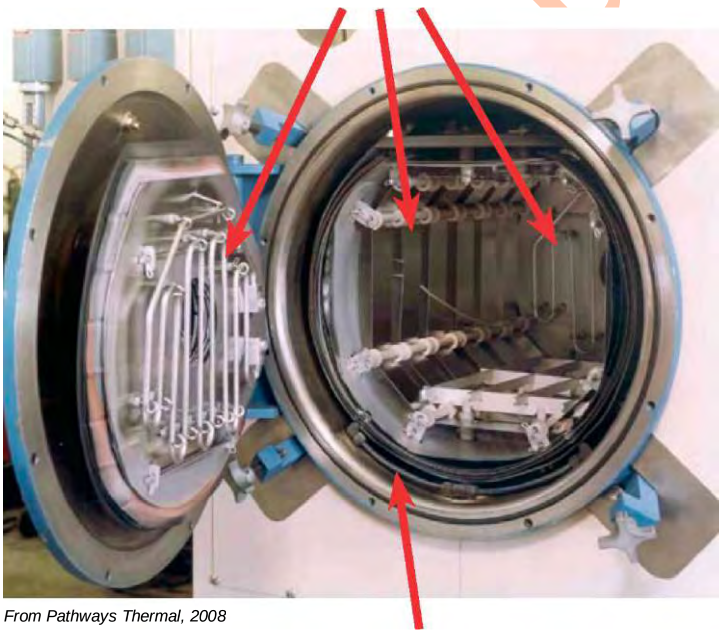
By placing multiple heating elements into a given space, the furnace can have multiple zone control for temperature. For example, a furnace could have 3 different zones of heating. One for each end, and one for the middle. The ends will most likely cool faster and heat up slower due to lack of proper radiant heat control within the hot zone. By employing multi-zone control, the furnace can compensate for these losses and provide a more uniform heat zone. With the typical insulation packages used, temperature uniformity in these types of furnaces is on the order of ±20° F.

Furnaces can have any number of atmospheric control options including inert gas, high vacuum or a combination. High vacuum pumping times and therefore the total cycle time is partially a function of the insulation used in the furnace. Typically graphite or ceramic "wool" materials may be used which have very high surface-to-mass ratios. These materials tend to trap oxygen inside of the chamber reQuiring longer pump down times and may cause outgassing during the heating process. This outgassing may be detrimental to the diamond brazing process if it is not effectively removed by the pumping system.

The energy efficiency of electric furnaces range from 10 to 70 percent. Since most of the types of furnaces used to braze diamond would be vacuum furnaces, the bulk of the energy waste is in the conversion losses.[7]

Maintenance and operational costs are relatively high for these types of systems. This is due to the fact that the resistive elements must be periodically replaced. The freQuency of replacement is a function of operating temperature, hours of operation, and cleanliness of the process. Brazing with paste is a "dirtier" process than foil due to the binders used.

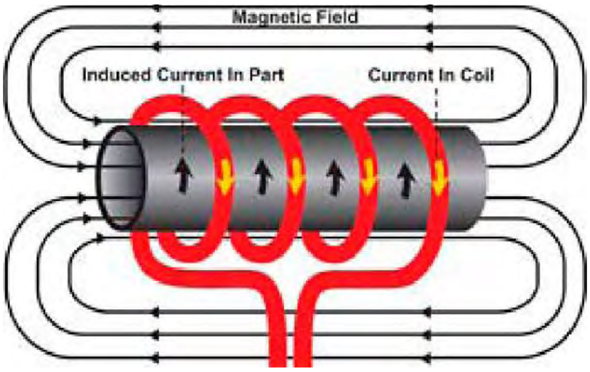
Typical small brazing vacuum furnace. From Nakanihon-Ro Kogyo.



From Pathways Thermal, 2008

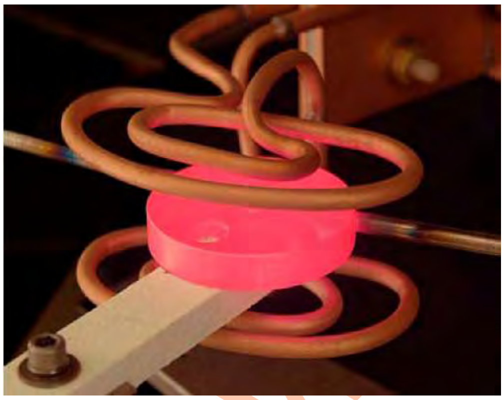
Induction

The basic principal of induction is based upon Faraday's Law. If a secondary of a transformer is located within the magnetic field of the primary, an electric current is induced in the secondary.



In a basic induction heating setup, a solid state RF power supply sends an AC current through a copper coil, and the part to be heated is placed inside the coil. The coil serves as the transformer primary and the part to be heated becomes a short circuit secondary. When a metal part is placed within the induction coil and enters the magnetic field, circulating eddy currents are induced within the part. As shown above, these eddy currents flow against the electrical resistivity of the metal, generating precise and localized heat without any direct contact between the part and the coil.

For sensitive brazing operations such as brazing diamond, an induction-based system may be fitted with an optical pyrometer to facilitate closed loop temperature control. Through proper selection of the induction heating power supply, temperature controller, and optical pyrometer, temperature control of ±2° F is routinely achievable.



Part being heated for brazing by induction

Temperature uniformity is achieved through coil design. The most effective uniformity can be achieved in round parts. Due to the nature of electrical current path flow, sharp edges could preferentially heat if the proper coil design is not used.

Induction coils are routinely placed into both high vacuum and inert atmosphere systems. Alternatively, as with infrared systems, the induction coil can be located outside of a Quartz tube. In this set-up the Quartz tube houses the part and is atmospherically controlled. The electromagnetic energy from the induction coil penetrates through the quartz tube and couples to the part. Unlike infrared systems, there are no losses through the Quartz tube, because the Quartz tube is not heated.

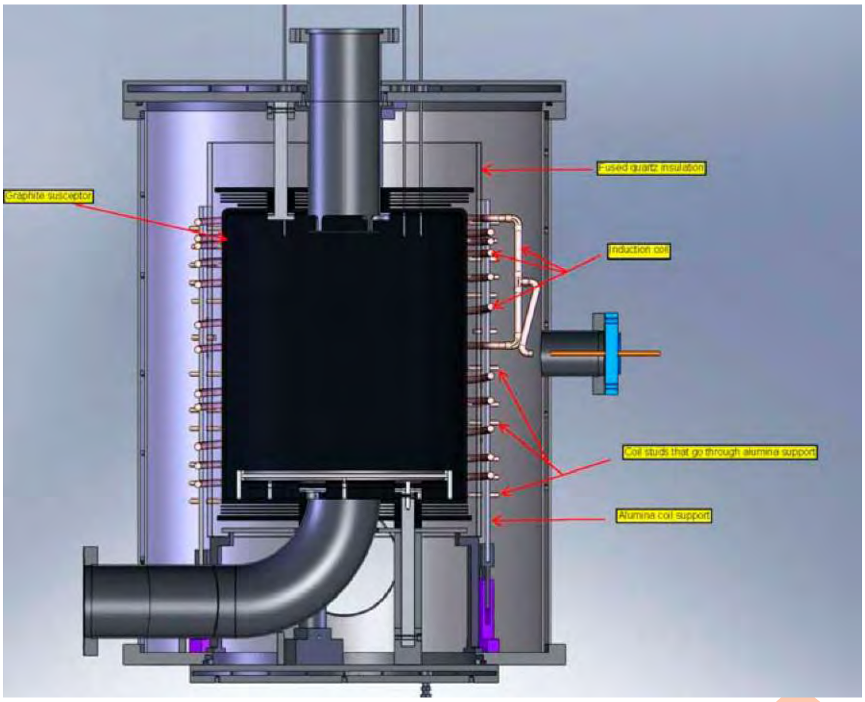
Due to the mechanism of heating, the typical energy efficiency is on the order of 80 — 90%.

Maintenance and operational costs are generally considered some of the lowest between other heating technologies. While the initial capital cost are higher than other systems the total cost per part must be evaluated. With this analysis, induction based systems typically show very high values.

Induction Furnace

An induction based furnace is very similar to the resistance based furnace discussed above with the exception of the heating mechanism. In an induction furnace a graphite susceptor is heated via induction. The susceptor then radiates heat to the part to be brazed.

Unlike resistive furnaces, induction based furnaces of sizes typically used for brazing diamond, do not have multiple zones. Temperature uniformity is achieved through coil design and insulation. Typical uniformity in these types of furnaces is on the order of ±15° F.



Cross section of an Induction High Vacuum Furnace

Like resistive furnaces, induction furnaces can have any number of atmospheric control options including inert gas, and high vacuum or a combination. Unlike resistive furnaces, some induction based furnaces use solid forms of insulation which minimize the surface area, thereby greatly decreasing the time required to achieve the desired vacuum level. Additionally, during the outgassing of the brazing process, solid insulation facilitates effective removal of any brazing by-products.

Very high levels of temperature control are achievable in these types of systems due to the solid insulation schemes used and the fast response of the induction heating system. These systems have a very high surface-to-mass ratio, which means that they can very quickly respond to desired temperature changes. Alternatively, typical resistance furnaces have very low surface-to-mass ratios, which make them very sluggish with respect to temperature change requests.

Induction-based systems are more energy efficient than resistance types due to the minimal losses during conversion. Based upon a 50 kW induction system, the typical cost for operation of an induction-based furnace is on the order of $1.00 to $1.50 per hour. This price is dependent upon local energy and inert atmosphere costs.

Unlike resistance-based systems, the maintenance costs are relatively low. Induction-based systems do not require the frequency of hot zone replacements that resistance based systems do. This is due to the fact that induction systems are non contact — they do not require the direct connection of electrodes. These connections in the resistance-based systems are a source of failure and material degradation.