Liquid Interface Diffusion Bonding Applications for Joining Plastic Injection Die Molds with Conformal Cooling, Hot Runners, and other Venting Attributes

Norman Hubele, President, Die-Bond, LLC, a Division of Refrac Systems, Chandler AZ

Abstract

The following paper discusses using liquid interface diffusion bonding, as conducted within a vacuum hot press furnace, as the preferred method of joining layered die mold blanks that may contain conformal cooling, venting, and other “hot runner” passages. Discussions about process methods and distinctions when using a vacuum hot press furnace, particularly compared to conventional vacuum furnace brazing, during the mold joining operations are made.

Introduction

Approximately 30 years ago it was a closely guarded secret within the injection molding industry that adding conformal cooling passages that wrap around the mold cavity made serious improvements to both mold cycle time and reduced part warpage. Vacuum brazed mold blanks containing cooling lines that specifically wrapped around the mold cavity were developed in Germany and run for the contact lens mold manufacturing industry as a closely held secret. Ten years later, the technology was re-developed by the cell phone manufacturing industry, and was used to make the early “Flip” phones and other very high volume telecom components. Jumping forward another five years later, the use of conformal cooled molds became a “white world” process technology that was widely published and it has been widely adopted by the worldwide plastics molding industry. Much less is widely understood about the methods used to join the layered mold elements that make up a finished “conformally cooled” mold blank.

From a fundamentals perspective it should be understood that that the lamination and joining of multiple 2-D layers made up of machined “wrought” bar stock materials is actually an additive manufacturing method, but it is not one based on using powder metal as the feedstock. A lot of material has been written over the last few years about 3-D additive manufacturing methods being applied to the manufacturing of conformal cooled molds, but as of this publication it has not found wide acceptance for manufacturing production molds, except for possibly validating design concepts and building prototypes. It remains to be seen if 3-D additive technologies will ever supplant the conventional 2-D layered additive manufacturing for mold making, but this author believes that the fundamental cost issue with having to make powdered metal first, and the resulting “as-cast” microstructure and possible resulting leaks paths makes this very unlikely.

2-D Layered Mold Joining Methods

The method used to laminate and join a lot of two dimensional (2-D) machined layers to form a 3-D mold containing many passages running in directions that may not otherwise be easily

SPE ANTEC® Anaheim 2017 / 1903
machined, is a key consideration when designing molds. For many years various creative mold designers have used very complex “cross drilled” hole systems that get “welded over” later in the manufacturing cycle to form interconnecting passages. Many mold shops started using conventional vacuum brazing methods to join multiple layers together as a way to minimize the weld distortion. To the present time, many mold shops are still using conventional vacuum brazing as the method to assemble their complex cooled molds.

Much information has also been written about the process known as “Diffusion Bonding” which is also known as “Diffusion Welding” in the welding community, and “Thermo-Compression Bonding” in the semi-conductor wafer fab industries. In most cases each of these specialized application areas have minor subtle differences, but all have similar overlapping furnace technology requirements. The purpose of this paper is to explore using a vacuum hot press furnace as needed to achieve good quality diffusion bonding, and to make note of how this technology can be better utilized for joining conformally cooled injection die molds. Various different approaches to achieving good bonds are made utilizing different kinds of furnace equipment which will also be discussed. Firstly, let’s discuss the types of braze joints and diffusion bonds that are made and what it means in terms of thermal heating profile that is utilized as shown in Figure One below.

Figure One: Thermal Profiles of Typical Bonding Methods
• **Conventional Vacuum Brazing:**

In this method two or more part layers are joined together by inserting a braze alloy (B-material) at the bond lines and the parts are heated up to above the melt point (liquidus) of the B-material. The holding time for the parts above the melting point of the braze alloy material, can vary from a very short hold time (2-5 minutes), to a much more extended hold time (2-4 hours typical), as may be needed to allow for diffusion of the parent metal into the braze joint for added strength.

• **Solid State Diffusion Bonding:**

In this method, two or more, mating parts are joined together without the use of an interface aid (or a B-material such as a braze alloy foil, plating, sputtered film, ion implanted layer, or other material foil). By definition a solid state bond is defined as the joining of two materials without the use of any other interfacial material or treatment, and that the resulting interface must be joined at or below the melting point of either parent material or any resulting eutectic that may form (T_{bond} < T_{Eutectic} – and this assumes that two different materials that could form a eutectic are present).

In this bonding method it is pretty normal to have 50% increase in grain size (or more), and require 2-4% total part strain in order to achieve good quality hermetic bonding, even for parts of relatively good surface finish. To achieve good bonding, considerable load or unit normal force must be applied to the bonding surfaces. Otherwise, one must expect to have a much larger grain growth than what might otherwise be employed.

• **Activated Diffusion Bonding:**

In this diffusion bonding method, the surfaces to be bonded are coated with a second “B” material, typically having a smaller atomic diameter, and higher vapor pressure, than the parent materials. The resulting diffusion bond is enhanced by the extra diffusion and mass transport rate that would otherwise be experienced during a solid state diffusion bond. In this method, and it is also by definition, that this type of bond is also run at or below the melting point of either parent material or any resulting eutectic that may form (T_{bond} < T_{Eutectic}A+B).

This process is routinely done on materials that suffer strength disadvantages from having any significant grain growth, or where the structure may not be strained as much during bonding. Structures that may have a high hermeticity requirement, that have poor surface finish, or that may be degraded by any grain growth (such as many nickel and cobalt based super alloys) are typically bonded using this method. Also, this method is particularly useful when the structure contains very small embedded passages that may be prone to plugging by any liquid generated during the bonding operation.
• **Liquid Interface Diffusion (LID) Bonding:**

In this bonding method, one purposefully places a second “B” material at the bond interface, with the intention that it will go liquid during the bonding operation. Arguably this is semantic with conventional vacuum brazing, but it should be stressed that there are still some significant differences between the two. Specifically, in the liquid interface diffusion bond, the starting interface is typically very thin (on the order of 0.00015 inches or 3.81 microns) where a typical braze joint usually starts at a thickness of 0.0015 inches (38.1 microns) or more. As the starting thickness is very thin, it is also normal that during the LID diffusion bonding process, the second “B” material is nearly completely diffused out into the lattice of the parent material by the end of the thermal process. It is also helpful to think about the fact that the liquid may be easily squeezed outward into the surface asperities, helping to minimize the voids that may otherwise be caused from parts with poor surface finish, or minor burrs.

In a typical braze joint, (even a normal diffusion brazed joint) the microstructure typically shows a defined layer of the braze alloy chemistry, and has fillets at the outer interfaces at each layer. The resulting strength of the diffusion brazed joint, and the liquid interface diffusion bond joint, can often vary by substantial amounts, due to relative amount of actual parent-to-parent metal bonding that actually occurs across the much thinner bond joint thickness. It should also be stressed that the added LID bonding layer may be chosen to form a eutectic with the parent metal, such that the bonding temperature can be conducted at just above the eutectic liquidus of the resulting system (T_{bond} > T_{Eu} or T_{liqB})

As the resulting diffusion rate for this type of bonding is also driven by a liquid, it typically occurs 3-5 orders of magnitude faster than the diffusion rate for a solid state bond, and as a result, may be done much more quickly, and at much lower strain energy, than is required for either the solid state or activated diffusion bonding methods. It is typical that this method is used for large parts with large internal passage geometries (over 1/8” nominal passages) where the risk from un-wanted plugging of the passages are minimized, or where the bonding cost needs to be as low as possible, or where the part size means that there may not be enough mechanical force available from the differential expansion tooling or hydraulic system/rams to achieve a good bond by any other method. By running this process with an extended hold time (3-4 hours typical) it is quite easy to establish bond strengths of >80 % of the parent metal tensile strength properties

• **Transient Liquid Phase (TLP or TLID) Diffusion Bonding:**

In this bonding method, the surfaces may by similar in quality and chemistry to the thin layer LID bonding method, but the process is simply slowed down enough to prevent liquid from actually forming to any significant level. It should always be remembered that the process heating rate can be slowed down enough that the parent metal
diffusion into the braze alloy or plated layer can be sufficient to retard the actual melting of the braze alloy or in-situ eutectic that may be formed. As a result, the risk of plugging a small passage can be substantially reduced, while otherwise still allowing the successful bonding of parts that may have a poor surface finish.

The slow ramp heating rate can be continued well above the TsolB of the second material to temperatures well above the TliqB of the interface system, provided that the ultimate temperature never exceeds the incipient melt point of the parent material (Parent Tsol). A typical microstructure for 420 series stainless steel injection molding dies bonded using thin BNi-2/AMS 4777 Metglas foil and a short cycle time LID bond process is shown in Figure 2 below:

As may be noted the LID bond joint is still quite thin, and shows very good diffusion interfaces with the parent material. It must be stressed that this type of bond can be used directly adjacent to passages that are 1/16” x 1/16” in size with very little risk of plugging, as the actual amount of liquid that is generated using the slow ramp rate of +30 F/Hour does not make much actual liquid (no substantial alloy filleting). It is noteworthy that at the 400 PSI unit normal stress that was used for this bond, very little parent metal strain was noted (less than 0.1% strain!!) and only a small percentage of the alloy (Which started at 0.0015” thickness) was actually displaced.

Figure 2. LID Bond microstructure of 420 Stainless Steel bonded with 0.0015” Thick Metglas MBF 20 foil at 1980 F - 1 Hour Hold with the ramp rate above the alloy solidus (1776 F) set at +30 F/Hour, loaded at 400 PSI unit normal stress all at 10^-5 Torr Vacuum (500 X Mag).

Figure 3. Same LID bond microstructure shown above at 1,000-X Mag showing a well diffused bond line and no bond line porosity.
Equipment Requirements for Diffusion Bonding:

Diffusion bonding can easily occur when it is not desired, anytime parts are held at a sufficient temperature to cause interatomic diffusion in a truly reducing atmosphere that can remove the nascent bound oxygen layers present on the surface of most metallic parts. As a result diffusion bonding can readily be conducted in a vacuum or reducing atmosphere furnace where the surface oxides are all reduced by the furnace operating atmosphere (Please see more information about the Ellingham Diagram at: http://www.engr.sjsu.edu/ellingham/ as Hosted by San Jose State University).

In general the vacuum reducing atmosphere pressure can be brought down very close or just below the boiling point of any of the major alloy constituents under vacuum (Think: Chromium!!). In this way, the mass transport rate for the highest vapor pressure alloy constituent can be easily harnessed to improve the bonding rate and quality.

Many vacuum brazing operations are conducted where simple dead weights are applied inside the furnace, as a method to insure all asperities on the surface of the bond interface are brought in intimate contact. Unfortunately, this does not always work as intended. For thicker parts where any residual machining stress may cause the parts to stress relieve in the “out of flat condition,” the total required force may be impractical because the force is too close to the yield strength of the material when hot. Historically, many users of conventional vacuum brazing technologies using dead weight loading have experienced scrap rates exceeding 20% of the quantity of parts being joined.

Over the years, the need for higher loads has resulted in the routine use of tooling methods that make use of either a differential expansion mismatch (Think: Put a high CTE part inside a “caged tool” that is lower CTE as needed to generate loading) or some type of active loading system, such as a pressure bellows or hydraulic ram system that can be used to apply a larger load as may be needed. For the case of using “caged tools” that are often bolted together, the user needs to understand that the maximum bond load is often generated before the part actually gets to the full bonding temperature, as the bolts or other structural members typically begin to yield at fairly low temperatures.

The need for better control of atmosphere and applied load stress has led to the development of the vacuum hot press system (VHP). A VHP is really just a conventional vacuum furnace with added features. As a result, a very large effective load may be applied using “hot rams” that come inside the furnace in similar fashion as any conventional arbor press does, typically working on flat platens to distribute the load uniformly on the part bond surfaces. The advantages that come with being able to apply the much larger unit normal “flattening” force only after the parts surfaces are reduced back to pure metal are substantial, including dramatically improved part surface finish and flatness post bonding, as well as reduced scrap rates.
Recent advances in the diffusion bonding industry have led to the development of a vacuum hot press (VHP) that also includes a Gas Fan Quench (GFQ) cooling capability as well, such that parts may be diffusion bonded and then directly quench hardened. Most plastics injection molds require quench hardening to optimize the post bond hardness and other raw material properties. Quenching may also be used to set the material up in the solution annealed condition, or otherwise to be set up for post bond aging.

Refrac Systems in Chandler, AZ is presently funding Solar Manufacturing, Souderton, PA and Beckwood Press/Triform, St. Louis, MO, to build what is thought to be the world’s first vacuum hot press system that includes the gas fan quench cooling option (known as a GFQVHP system) as shown below in Figure 4:
The world’s first Gas Fan Quench Vacuum Hot Press (GFQVHP) furnace system was specifically designed to take large multicavity injection die molds sized up to 36” wide x 24” tall x 50” long and both diffusion bond at up to 100 tons of applied load with gas fan quench heat treatments available for the completed assembly all in one run.

Closing Remarks:

There are considerable challenges confronting manufacturing and process engineers in selecting the best bonding process for their conformally cooled dies. It takes a great deal of engineering experience to understand the trade-off’s between the thickness of the second “B” material, the maximum allowable ramp heating rates and loading profile. Small flow passages are particularly problematic to avoid the risk of passage plugging, while minimizing the overall process time. It is always recommended that any mold manufacturer should consult with its bonding source before cutting any chips for a new mold. Refrac Systems acting thru its wholly owned subsidiary Die-Bond LLC, is always ready to help any prospective mold manufacturer with the proper design and process selection to insure the highest quality bonding can be achieved. You can
reach Die-Bond, LLC, at 6141 West Erie, Street, Chandler, AZ 85226, Phone: 480-940-0024 or thru its parent company: Refrac Systems, at 7201 West Erie Street, Chandler, AZ 85226, Phone: 800-4-REFRAC / 800-473-3722.