Computer Assisted Induction Aluminum Brazing

Abstract

Induction aluminum brazing is becoming more and more common in industry. A typical example is brazing various pipes to an automotive heat exchanger body. The induction coil widely used for this type of process is non-encircling one, which can be referred to as "Horseshoe-hairpin" style. For these coils, the magnetic field and resulting eddy current distribution are inherently 3-D in nature. In these applications, there are problems with joint quality and consistency of the results from part to part. To solve one such problem for a large automotive manufacturer, Flux3D computer simulation program was used for the process study and optimization. Optimization included changing the induction coil and magnetic flux controller configuration. New induction coils, which have been experimentally validated in a laboratory, produce parts with higher quality joints in several production sites.

Introduction

Each car requires several different heat exchangers (heater cores, evaporators, condensers, radiators, etc.) for powertrain cooling, air conditioning, oil cooling, etc. The vast majority of the passenger car heat exchangers today are made of aluminum or aluminum alloys. Even if the same engine is used for several automobile models, the connections can vary due to different layouts under the hood. For this reason, it is standard practice for parts manufacturers to make several basic heat exchanger bodies and then attach different connectors in a secondary operation.

Heat exchanger bodies usually consist of aluminum fins, tubes and headers brazed together in a furnace. After brazing, heat exchangers are customized for the given car model by attaching either nylon tanks or most commonly different aluminum pipes with connection blocks. These pipes are attached either by MIG welding, flame or induction brazing. In the case of brazing, very precise temperature control is required due to the small difference in the melting and brazing temperatures for aluminum (20-50 C depending upon alloy, filler metal and atmosphere), high thermal conductivity of aluminum and short distance to other joints brazed in a previous operation.

Induction heating is a common method for brazing various pipes to heat exchanger headers. Figure 1 is a picture of an induction brazing set-up for brazing a pipe to a tube on a heat exchanger header. Due to the requirements for precise heating, the face of the induction coil must be in close proximity to the joint to be brazed. Therefore a simple cylindrical coil can not be used, because the part could not be removed after the joint is brazed.

There are two main induction coil styles used for brazing these joints: "clamshell" and "horseshoe-hairpin" style inductors. "Clamshell" inductors are similar to cylindrical inductors, but they open to allow part removal. "Horseshoe-hairpin" inductors are shaped like a horseshoe for loading the part and are essentially two hairpin coils on opposite sides of the joint.

The advantage of using a "Clamshell" inductor is that the heating is more uniform in circumference and relatively easy to predict. The disadvantage of a "Clamshell" inductor is that the mechanical system required is more complicated and the high current contacts are relatively unreliable.

"Horseshoe-hairpin" inductors produce more complicated 3-D heat patterns than "Clamshells". The advantage of a "Horseshoe-hairpin" style inductor is that the part handling is simplified.

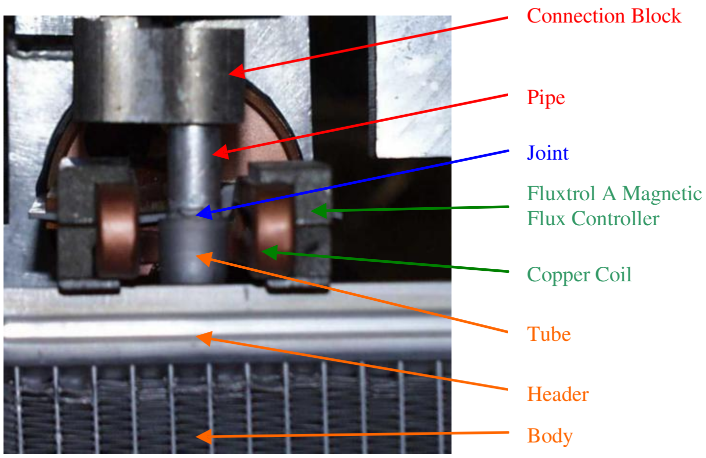

Figure 1. Setup for induction brazing of a heat exchanger joint using a "Horseshoe-hairpin" style inductor

Pipe to Tube Brazing Process Optimization Using Computer Simulation

A large heat exchanger manufacturer was having quality problems with brazing the joint shown in Figure 1 using a "Horseshoe-hairpin" style inductor. For the majority of parts, the braze joint was good. For some of the same parts, the heating would be absolutely different and it would result in insufficient joint depth, cold joints, or filler metal running up the pipe wall due to local overheating. Even with testing of each heat exchanger for leaks, some parts were still leaking at this joint in service. The manufacturer hired Centre for Induction Technology, Inc. to analyze and solve this problem.

The power supply used has variable frequency of 10 – 25 kHz and rated power 60 kW. An operator installs the filler metal ring on the pipe end and inserts the pipe inside the tube. After that he places a heat exchanger on a special rig and moves it inside the "horseshoe" inductor. The whole brazing area is prefluxed. Power turns on and heating begins. Typical frequency is 12 -15 kHz and the heating time is around 20 seconds. Power level is programmed with linear reduction at the end of the heating cycle. Optical pyrometer turns power off when temperature on the back side of the joint reaches a preset value.

There are many factors that can cause the inconsistency the manufacturer was experiencing, such as variation in joint components (dimensions and position), unstable and variable in time contact between tube, pipe and filler ring, etc (electrical and thermal). Some phenomena aren't stable by nature and small variation of these factors can cause different process dynamics. For example the open filler metal ring can partially unwind under the electromagnetic forces. The "free" end of the ring may be sucked back by capillary forces or remained unmelted. The noise factors are difficult to eliminate or reduce and the solution must be in increasing of the whole process robustness. Computer simulation is an effective tool for the process analysis and optimization.

In the process of experimental study of brazing process, strong electrodynamic forces were observed. At the moment of power on, the horseshoe coil experiences a clear expansion due to a sudden application of electrodynamic force. Measures were taken to make the inductor mechanically stronger, including additional fiberglass (G10) plate connecting the roots of two hairpin coils. The other demonstration of electrodynamic forces was in shifting of molten filler metal away from the areas close to copper turns where magnetic field is stronger. In normal process filler metal distributes uniformly around the joint due to capillary forces and gravity. In non-proper process, filler metal may be spilled or moved up along the pipe surface.

Because aluminum brazing is a very complicated process, we can't expect accurate simulation of the whole chain of mutually coupled phenomena - electromagnetic, thermal, mechanical, hydrodynamic and metallurgical. The most important and controllable process is electromagnetic and it was analyzed using Flux 3D program. Due to the complex nature of the induction brazing process, a combination of computer simulation and experiments were used for process design and optimization.

Analysis of Existing Induction Brazing Process

A common rule of thumb in induction heating is that the heating pattern resembles the shape of the induction coil and the highest temperature is closest to the induction coil face. For the problem studied, it was not true. While it was not possible to measure the actual temperature distribution in the manufacturing facility, indirect evaluation could be made by looking at the surface of the part. The surface of the aluminum, which reached close to the brazing temperature would be a different color after the process was completed. Microscopic evaluation of the braze joints showed that this coloration line was a good indicator of internal joint depth. According to the color and microscopy, the braze depth for good parts was deeper at the front and back of the joint than on the sides, which were closest to the induction coil. This fact looked strange for induction heating.

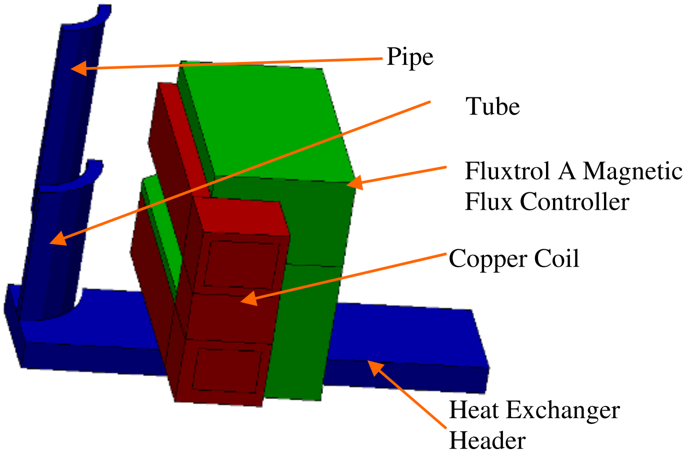

Figure 2. Geometry used for 3-D electromagnetic computer simulation

As discussed above, it is not possible to model all of the phenomena involved in the brazing process, so the main variables used for comparison were eddy current distribution, power density distribution and total induced power in the different pieces (pipe, tube and body). To keep the problem manageable for simulation, ¼ of the system was used (Figure 2).

In the problem formulation, two main variables were discovered that had a significant influence upon the distribution of power in the system: coil crossover and joint contact. The way the crossover was made that connected the two "hairpin" coils of the "Horseshoe-hairpin" inductor has a very strong influence on the electromagnetic system description. The crossover used in production connected the two "hairpin" coils diagonally. This meant that the pipe and tube were exposed to a "transversal" magnetic field. If the crossover were made horizontally, then the tube would be exposed to a "longitudinal" electromagnetic field (Figure 3). The difference between these two systems was studied by changing the boundary conditions along the centerline.

The second factor was the electrical contact in the joint area. As discussed above, before the filler metal is molten, the contact in the braze joint is uncertain. With the induction coil that the manufacturer was using that had a diagonal crossover, the current paths and induced current density distribution would be significantly different for good and bad contacts (Figure 4). This is because the current flows from the pipe to the tube when the electrical contact is good. When there is no contact, the current must wrap around the inside of the tube in order to be continuous. During the process of heating the aluminum expands and the electrical contact improves and when the filler metal flows then there is good contact. This means that if there is some partial electrical contact or if contact is established at different times, heating dynamics can be significantly different. The simulation also shows clearly that the highest temperature should be on the front and back of the tube and not on the sides as is shown in practice due to higher current density, though local overheating of the tube edge near the face of the induction coil may be observed at the beginning of heating.

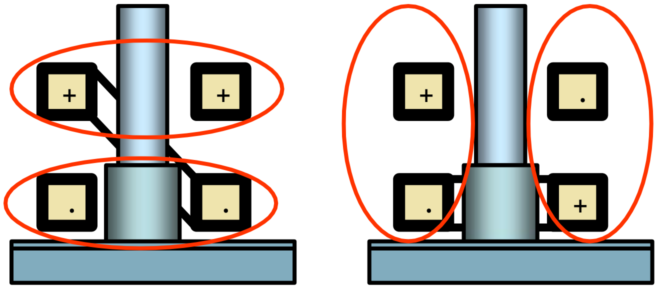

Figure 3. Influence of the crossover on magnetic field pattern (diagonal crossover left, horizontal crossover right).

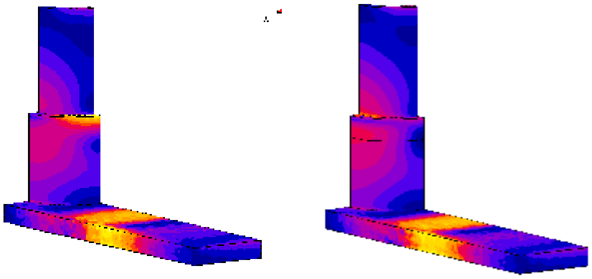

Figure 4. Induced current density in the joint area for the existing coil with no (left) and good (right) electrical contact in the joint area and a diagonal crossover

The current density distribution for the same induction coil geometry, but with the horizontal crossover is shown in Figure 5. The difference between the current density distributions with no contact (left) and good (right) is much smaller than for the diagonal crossover, which is desirable. This means that the process is less sensitive to contact in the joint area. However, much more power is induced in the header and much less in the joint area. This will lead to a much slower brazing process.

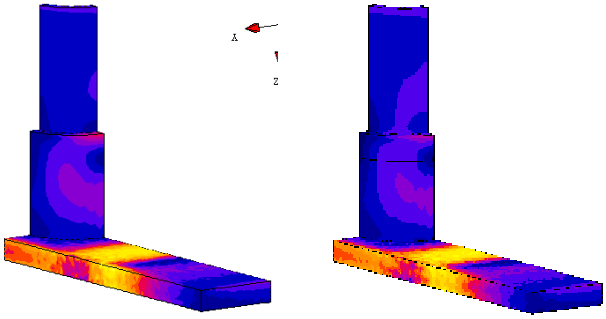

Figure 5. Induced current density in the joint area for the existing coil with no (left) and good (right) electrical contact in the joint area and a horizontal crossover

Design of Optimized Induction Brazing Process

CIT determined that there were several steps to take in order to improve the robustness of the induction brazing process. The first was to use the horizontal crossover to reduce the sensitivity to joint contact and part position inside the inductor. Due to production demands, a longer cycle time was not an option, therefore the distribution of power in the joint area had to be changed significantly. Therefore, more power had to be shifted from the tank to the joint area. Compared to the distributions shown in Figure 4 for the existing coil, more power should be moved to the tube to prevent filler metal runup and promote the filler metal to flow deeper into the joint, reducing the probability of a defect.

In order to shift more power from the tank to the joint area, the copper coil and magnetic flux concentrator dimensions were modified. The main change was the addition of a 1.5 mm thick piece of Fluxtrol A to the bottom of the lower turn to shield the header from the magnetic field and focus the current density in the joint area. Figure 6 shows the induced current density distribution for the optimized induction coil. Much less power is induced in the header relative to the tube and pipe. At the same time, the area of high current density is lower in the tube, which will lead to deeper joint depth.

A prototype induction coil was made based upon computer simulation. With only minor modification of the magnetic flux controller dimensions, high quality joints with greater depth were made in the laboratory and production settings. It was found also that by modifying slightly only the magnetic flux controller dimensions, the induction coil could be used for brazing the whole family of pipes that were attached to the header. In addition to improved joint quality and consistency, the optimized inductors have lower cycle times (15-30% less depending upon connector type) and reduced energy usage. This family of inductors has been successfully installed at several plants for brazing several different joints.

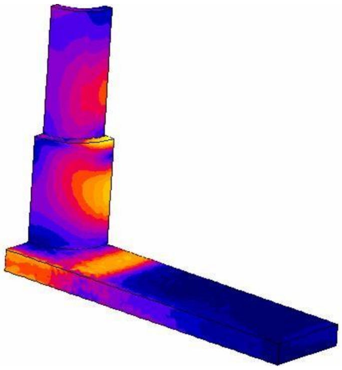

Figure 6. Induced current density (left) in the joint area for the optimized coil (right)

Conclusions

In brazing applications especially in aluminum brazing, computer simulation can't predict accurately the entire process dynamics and results due to a set of mutually coupled phenomena, some of which are very difficult to describe mathematically. Coupled electromagnetic and thermal simulation should provide sufficient basis for process optimization and quality improvement. At the time of the development, we had no opportunity to use coupled EM and thermal simulation of 3-D geometries and only 3-D electromagnetic program has been used for calculation and optimization of induced power distribution in joint components. New geometry of induction coil has been proposed, which might be used for brazing of a whole family of joints with adaptation to particular application by variation of magnetic flux controller geometry. Practical experience shows that electrodynamic forces in brazing system are high and must be taken into account in induction coil design. Practical use of designed inductors in several production sites showed very good quality and consistency of the results.