Coil life depends heavily on satisfactory cooling of the coil during operation. Determining localized copper temperatures, temperature distribution in the copper winding, and the effects of duty cycle provide a basis for optimizing coil design.

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Tooling failure is a leading cause of induction heating-machine downtime. Three main classes of induction heating tooling failures are electrical breaks, mechanical damage, and thermal degradation [1-4].

Electrical breaks may be caused by different factors such as including insufficient insulation between the coil turns, insulation wear, and magnetic chips attracted to the conductors. This failure mode can be prevented by proper design and maintenance of the coil.

Mechanical damage results from inaccurate coil setup resulting in part impact, incorrect machine operation, electromagnetic forces, and thermal distortion of coil components. The coil can be damaged instantaneously by breaking coil integrity and causing water leakage, or coil dimensions can change gradually. For example, a copper coil may be out of specifications due to metal creep, which can result in loss of the heat pattern. In many cases, mechanical failure is preventable with the proper precautions and maintenance on the machine.

Failures due to thermal degradation are more challenging to resolve. Thermal degradation is caused by localized or total overheating of the coil head due to eddy-current losses in the copper, magnetic losses in the flux concentrator, and by heat transfer from the hot surface of the part by convection and radiation. Overheating can result in copper cracking or deformation, as well as concentrator material degradation. Copper cracking usually occurs due to thermal stresses in hardening coils with a short cycle, while gradual coil deformation is more typical for continuous processes. Thermal influences can strongly increase the effects of electromagnetic forces and accelerate aging of electrical insulation.

Copper overheating is the leading cause of failure in heavily loaded hardening inductors, which is the main focus of this article. In coils manufactured with consistent quality, copper cracks occur in nearly the same location on an inductor each time and within a certain range of parts produced.

Ways to Extend Coil Life

Approaches used to increase coil life include providing additional cooling, reducing the density of heat sources, and changing the coil design completely.

Additional cooling is provided by increasing the water flow rate, adjustment of the water pocket, and introduction of additional cooling circuits. Water flow rate is the first step, and it can be increased until the pump output limit is reached. Inductor manufacturers generally have internal guidelines related to best practices for water pocket and cooling circuit design, which have been developed through experience. Further increases in flow rate may require a larger pump or adding a booster pump to the system.

A limit is reached on some very high power density coils, where coil life is unsatisfactory using even the best cooling circuit design and very large pumps. At this point, it is necessary to try to minimize the localized power density in the weak point of the inductor. This is challenging in complex inductors because changing this section may affect the heat pattern in this area of the part, as well as in the rest of the part.
Resolving inductor thermal degradation failures is based on practical experience, and in many cases requires several iterations. There is significant cost associated with each of these tests (prototype coils, additional pumps, machine downtime, test parts, met lab time, etc.), which typically are not budgeted.

A more scientific method, which would reduce the number of iterations and optimize equipment purchases, is of great value. Furthermore, using this method up front in the coil development can avoid troubleshooting due to insufficient coil life occurring during the early stages of production.

Computer simulation is a natural tool for analyzing all influencing factors, such as fluid dynamics, heat transfer, electromagnetic, thermal, stresses, and structural transformations, that contribute to inductor failure by thermal degradation. While there is no one software program currently on the market with strong three-dimensional (3-D) coupling of all of these phenomena, there are simulation tools and analytical formulae currently available to tackle the problem in steps. Fluxtrol uses such a methodology to predict copper temperatures. The method is considered a good first approach to the problem and a basis for further improvements as software improves (see sidebar). The following case study demonstrates representative results.

Case Study: Seam Annealing

In the tube and pipe industry, heavy-wall tubes are commonly arc welded. The arc welding process changes the structure of the material in the seam area and the structure often is restored using a local annealing process (seam annealing). Induction heating is the preferred method for seam annealing after welding.

Figures 1 and 2 show parts of a coil drawing for seam annealing after spiral welding of large diameter tubes used in the oil and gas industry. The cross section in the heating area (Fig. 1) has a recess in the middle of the inductor to allow room for the bead that is formed during the

Predicting Copper Temperatures Using Computer Simulation

The methodology used by Fluxtrol to predict copper temperatures consists of an iterative 7 step approach:

1. Electromagnetic plus thermal simulation to optimize part heating and coil parameters
2. Coil engineering using CAD program
3. Analytical hydraulic calculations for the coil cooling circuit
4. Calculation of localized heat transfer coefficients in high power density areas of the inductor
5. Electromagnetic plus thermal simulation of coil component heating
6. If elevated component temperatures exist, return to step 2 to improve cooling circuit
7. If elevated component temperature exists, return to step 1 to improve induction coil geometry from a cooling perspective with minimal sacrifice in part heating or coil parameters

Computer simulation to optimize the induction coil based on part heating and coil parameters should be carried out first. If the life of a coil design based on this criterion is satisfactory, it results in minimum production cost.

In the coil engineering stage, busswork, leads, and complete inductor cooling circuit should be laid out, which is essential for the hydraulic calculations. The water cooling circuit can be broken down into several components. Pressure drops in every component of the circuit together with the additional pressure drop due to directional or flow-passage geometry change should be calculated. These numbers provide a flow rate and localized water velocities based on the pump pressure.

Using water velocities and tubing cross sections, it is possible to calculate Reynolds, Prandtl and Nusselt numbers for all of the different heating areas of the inductor. Heat transfer coefficients are calculated from the respective Nusselt numbers from the relationship

\[ \dot{\alpha} = \frac{Nu \cdot k}{D_e} \]

where \( \dot{\alpha} \) is heat transfer coefficient, \( Nu \) is Nusselt number, \( k \) is thermal conductivity, and \( D_e \) is equivalent diameter.

It is possible make a good approximation for the hydraulic and heat transfer coefficient calculations using an Excel spreadsheet. Both the hydraulic values and heat transfer coefficients are dependent on the bulk temperature of the cooling water in that section of the inductor. Power dissipated in the different sections of the inductor and simple calorimetric calculations for local water temperature are incorporated into the spreadsheet. The base data derived from the first four steps are used to simulate the inductor temperatures using an electromagnetic plus thermal simulation program.

In many cases, the procedure will only be five steps and further improvement is not required. That is, all inductor parameters are acceptable and no further modification is required.

In very heavily loaded applications, it is necessary to have an iterative process to resolve elevated temperatures in local areas of the inductor. The first step is to return to coil engineering to determine if there is a way to improve the cooling circuit to improve the high-temperature inductor areas. After updating the cooling circuit, redo hydraulic and heat transfer coefficient calculations, and repeat the simulation for the inductor temperature.

If unacceptably high temperatures still exist in the same components of the inductor, then it is necessary to return to the first step; i.e., computer simulation for induction coil design. It is necessary to make changes to the coil copper profile and to find a compromise between inductor performance and coil component heating. After creating a new design, the rest of the steps described above are carried out.

This method should be repeated until satisfactory temperatures are reached in all components of the induction coil.

Fig. 1 — Cross section of induction coil for spiral welded-tube seam annealing.
welding process. The top view of the inductor (Fig. 2) is shown as being flat, but the side view (not shown) shows the inductor is designed to follow the contour of the pipe.

For this case study, a large diameter pipe with 0.250 in. (6 mm) wall thickness is heated. The arc length of the “active” area the winding (not including the cross-overs or leads area) is 32.5 in. (825 mm). The process is continuous with a pipe feed rate of 7.4 in./s (188 mm/s). The frequency used for simulation is 1 kHz. Two different types of magnetic flux controller (laminations and Fluxtrol A) are considered. Flux 2D electromagnetic plus thermal software program is used for all heating simulations.

The conditions are the same maximum weld seam temperature of 1200°C ± 20°C (2190°F ± 36°F) exiting the inductor and desired equalized annealing temperature of 1000 to 1050°C (1830 to 1920°F) shortly after exiting the inductor. This area of high temperature should extend beyond both sides of the weld bead.

The first step in the procedure is electromagnetic and thermal simulation of the heating process. The coil is long and can be considered as a two-dimensional (2-D), plane parallel system. Due to symmetry, it is only necessary to simulate half of the induction coil.

Figure 3 shows the temperature of the pipe at the exit of the induction coil for a coil with laminations and three seconds after exiting the coil. An inductor power of 600 kW was required. The coil current was 18.8 kA in the main leg and 9.4 kA on each of the return legs.

To compare the performance of laminations to Fluxtrol A, the magnetic flux controller properties and the coil current required are changed to reach the same temperature in the same amount of time. Figure 4 shows the temperature distribution of the pipe at the exit of the induction coil for a coil with Fluxtrol A and 3 seconds after exiting the coil is nearly identical. The inductor power required is the same as for laminations; i.e., 600 kW. The coil current is slightly higher, being 20 kA in the main leg and 10 kA on each of the return legs.

While coil engineering follows simulation of part heating, an existing inductor was used in this study for which drawings already existed, so coil engineering was not required.

The next step involves hydraulic calculations, and the magnetic flux controller has no effect on the calcu-
lations. The inductor contains two water inlets and four outlets. Because there are two separate water channels in the main leg, we can consider the inductor as having four separate water circuits on this inductor for the hydraulic calculations. For a water pressure of 30 psi applied to each of the four water circuits, the total water flow rate is about 5.8 gpm per circuit or 23.2 gpm total (0.36 or 1.46 liters/s). This calculation takes into account the pressure drop in the inlet hose, the buss tubing, the bending areas, and the two active legs.

The local heat transfer coefficients can be derived after performing hydraulic calculations. Areas of interest are the main heating leg and the return leg. In the main water pocket, the water velocity is 12 ft/sec (3.65 m/s) and close to 19 ft/sec (5.8 m/s) in the return leg. Putting the losses in the inductor sections into the spreadsheet yields a temperature rise in the bulk water of around 13ºF (7ºC), which does not have a significant impact on heat transfer coefficients. Therefore, the heat transfer coefficients for the main leg and return leg should be 14,000 and 22,500 W/m²K, respectively.

To simulate the localized inductor temperatures, it is necessary to consider the inductor construction to calculate localized inductor loading. The power calculated in both cases is the same. It is necessary to recalculate for the space factor considering space unusable around the leads area, cross-overs and copper keepers. This has no effect on the total power, only on the required coil current.

For laminations, a 0.125 in. (3 mm) copper keeper is required every 4 in. (100 mm). Also, there should be at least a 0.250 in. (6 mm) gap between the laminate stack and the leads or the cross-overs to prevent overheating from the 3-D magnetic fields. This means that the effective length of the inductor is about 0.89 times ideal. To achieve the results calculated above, it is necessary to increase the coil current 5.7%.

Copper keepers are not required for Fluxtrol A. There is still a 0.75 in. (19 mm) wide busswork. The concentrator can come within around 0.0625 in. (1.5 mm) due to the better performance in 3-D magnetic fields, which means the effective length of the inductor is over 0.99 times ideal. Therefore, it is only necessary to increase the coil current by 0.4%.

After recalculation, the current in the coil with laminations is 1% lower than the coil with Fluxtrol A. This is a much smaller difference than 6% from the ideal inductors. Therefore, a current of 19.9 kA is used for the coil with laminations and 20.1 kA for the coil with Fluxtrol A.

Besides recalculation, it is also necessary to include losses in the concentrators and heat transfer between the copper and concentrator. Losses in the concentrator should be calculated based on flux density values from simulation of the part heating and input into the thermal block as a constant power source in Flux 2D. The process is continuous, so simulation should be run until steady state temperatures are achieved in all components.

Figure 5 shows the temperature distribution after 2,000 seconds for

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the coil with laminations, at which point the inductor is at steady state. The maximum temperature in the copper is 322°F (161°C) in the corner of the main leg. The temperature in the lower half of the laminations is nearly identical as a result of poor heat transfer between the laminations and the copper due to uncertain thermal contact and low conductivity filling resins. The temperature in the return leg is significantly lower due to lower losses, higher heat transfer coefficients, and shorter distance to the water cooling.

Figure 6 shows the temperature distribution in the coil with Fluxtrol A after 2,000 seconds, which is at steady state. The maximum temperature in the copper (again in the corner of the main leg) is slightly lower (311°F, or 155°C) compared with the coil with laminations. The overall temperature of the Fluxtrol A is significantly lower than the laminations due to good thermal contact with the copper for heat extraction due to exact material dimensions and the use of high thermal conductivity epoxies (Duralco 4525, Cotronic Corp., Brooklyn, N.Y., www.cotronics.com) [5]. As before, the temperature of the return leg is significantly lower than those of the main leg.

Based upon these temperatures, it is the opinion of the authors that both the inductor with laminations or Fluxtrol A would have good lifetime and no further optimization would be required.

For the sake of study, a case of 50% higher power in the inductor for both cases is considered. Coil current would be increased 22% for both cases and the losses in the concentrator would increase by 50%. Heat transfer coefficients used remain the same.

Figure 7 shows the temperature distribution after 2,000 seconds for the coil with laminations. The maximum temperature in the copper is 466°F (241°C) in the corner of the main leg. The temperature in the lower half of the laminations is nearly identical and there is a small spike on the outer corner. The temperature on the return leg is relatively low.

Figure 8 shows the temperature distribution after 2,000 seconds for the coil with Fluxtrol A. The maximum temperature in the copper is 433°F (223°C) in the corner of the main leg. The temperature in the lower half of the Fluxtrol A is lower than in the copper, but still elevated. There is no peak at the outer corner.

Figure 9 shows the temperature evolution over time for the coil with laminations and with Fluxtrol A in two critical areas of the coil, the copper corner and the center of the bottom of the concentrator pole for a continuous heating process.

When 50% higher power is used, both of these cases could be considered to be in the critical temperature range for thermal degradation. The copper temperature is around 33°F (18°C) less for the coil with Fluxtrol A. The temperature on the bottom of the Fluxtrol A is around 74°F (41°C) lower than on laminations. The difference in overall temperature of the concentrator is even greater. The lower temperatures present on the coil with Fluxtrol A should lead to extended coil life.

The above considerations are for a continuous heating process. From this data, some short evaluations are made about what could be expected during an intermittent heating process such as single-shot hardening. Figure 10 shows the heating dynamics in the first 10 seconds of heating.

All temperatures are lower than for the case of steady state. Note though, that the difference between the copper temperatures is much higher than in the case of a continuous process. The temperature of the copper in the coil with laminations is 72°F (40°C) higher than for the coil with Fluxtrol A. This has a dramatic effect on the coil life.

Concentrator temperature in this case is much lower than for continuous, and is considered to be in the safe range. This is only for one heating cycle. Further analysis will be made of the effect of cycling on the coil temperatures and will include running an intermittent process to steady state.

Note that due to the shape of the curves, it is clear that the main source of heating in the concentrator is conduction from the high-temperature copper. Therefore, the concentrator temperatures should be lower than the high-temperature corner of the
copper. This shows that keeping the coil copper cool will enhance not only the life of the copper, but the magnetic flux controller also.

Conclusions
Coil life can be compromised by mechanical damage, electrical breaks and thermal degradation. Problems related to mechanical damage or electrical break can almost always be solved with the proper maintenance procedures and machine design. Induction coil failures due to thermal degradation are more complicated. Reducing the induction coil component temperatures has a dramatic effect on the coil life. Practical methods for increasing the coil lifetime include raising water pressure and changes to the water circuit in the inductor. These adjustments are commonly made empirically based upon the experience of the induction coil designer.

A more scientific method to predict induction coil temperatures is based on an iterative approach using a combination of computer simulation, good engineering practices, and analytical calculations. This method can be used to improve an existing design or during new induction coil development.

This work establishes a foundation to study induction coil heating and further improves the state-of-the-art in induction coil design process. The method can be applied to any induction coil. Future studies on different induction heating applications using the method could lead to further improvements in induction coil life.

References


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Fig. 9 — Temperature evolution in critical areas of the induction coil with laminations and with Fluxtrol A for continuous heating.

Fig. 10 — Temperature evolution in critical areas of the induction coil with laminations and with Fluxtrol A for intermittent heating with 10 second on time.