Innovative Induction Heating of Oil Country Tubular Goods

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Tubular products manufactured for use in oilfield applications are in demand, and it is a demanding application. A newly developed and patented technology improves the induction-heating process used to produce consistent properties in these products.

Skyrocketing global demand for petroleum has driven aggressive efforts in oil exploration, transportation and environmental safety, resulting in greater demand for tubular products. A good indicator of increased oilfield activity is the Drilling Rig Report. The February 2007 rig count reports 1,714 working rigs in the U.S. This compares to 1,513 a year ago, 853 five years ago, 807 ten years ago and 653 fifteen years ago.[1]

High-quality tubular products are used to drill wells and turn them into producers. After the well is drilled, steel pipes (casing) are lowered into the hole and secured with cement. This provides a structural component of the well bore. Casing is available in a range of sizes and material grades. It is usually manufactured from carbon steel heat treated to obtain particular mechanical properties such as varying strengths – J-55 has a minimum yield of 55,000 psi and P-110 has a minimum yield of 110,000 psi – or a combination of properties. For special applications, casing can be fabricated from stainless steel, aluminum, titanium and other metals.

Fig. 1. Oil country tubular goods

Any mechanical failure of the pipe could result in the loss of the drill string down the well bore. Estimates of the cost to operate a drilling operation over an offshore deep-water site could reach as much as $500,000 per day. Lost drilling time as well as retrieval and environmental costs make connection integrity even more important because a mechanical failure of the well-bore casing could cause leakage into groundwater aquifers or other environmental catastrophes.

Taking into consideration the necessity of drilling deeper wells in combination with a harsh drilling and operation environment, the providers of casing and tubing demand higher-quality tubular products, including heavier-wall pipes and reliable connections.

Companies within the oil industry have developed proprietary thread designs that are supplied to oil- and gas-exploration companies. These are referred to as premium connections. These high-performance threads assure superior hydraulic sealing, improved tensile capacity and ease of makeup.

Premium connections are typically long tapered threads with separate sealing surfaces. The female end is referred to as the box, and the male end is called the pin. The manufacture of the connection begins with a straight length of pipe approximately 30-60 feet in length. The ends of the pipe are inserted into an upsetting press and mechanically formed to the rough taper of the thread.

Upsetting creates changes in the grain structure of the metal. Following the upsetting operation and in order to improve mechanical properties and prevent failure of the connection, the formed ends of the pipe undergo a specific heat-treatment operation (i.e., subcritical annealing, normalizing, stress relieving, etc.).

Stress Relieving

The stress-relief operation is an important step in the manufacture of a quality connection. Improper heat treatment could result in several undesirable phenomena from total joint failure to a type of bi-metallic corrosion known as "ring-worm corrosion" that occurs in improperly stress relieved or normalized pipes. This corrosion takes the form of a ring around the pipe usually located a few inches up from the pipe upset.

Stress relieving is typically done prior to machining of the thread. In order to achieve the best stress relief, the upset end must be uniformly heated along the entire swage length as well as through the entire wall thickness of the pipe. Superior axial and radial temperature uniformity is imperative for a quality product.

The ability to provide uniform heating, high quality and cost-effectiveness with induction-heating machinery has traditionally been the key benchmark deliverables in the past. Today these three are joined by a fourth requirement that is equally important. Flexibility of machinery reflects its ability to process a wide variety of parts without compromising product quality.

A modern connection manufacturer can have as many as 250 different pipe-diameter and wall-thickness combinations to thread. Pipe diameters can vary from 2.0625-18.625 inches (52-473 mm) with wall thicknesses ranging from 0.150-1.25 inches (3.8-32 mm) or more. In addition, the swage length can vary from 5-16 inches (127-406 mm) depending upon the pipe diameter, wall thickness and application specifics. Therefore, manufacturers of tubular goods are facing challenges to be able to improve flexibility of induction-heating systems while increasing productivity and improving heat uniformity when processing a variety of pipe sizes.

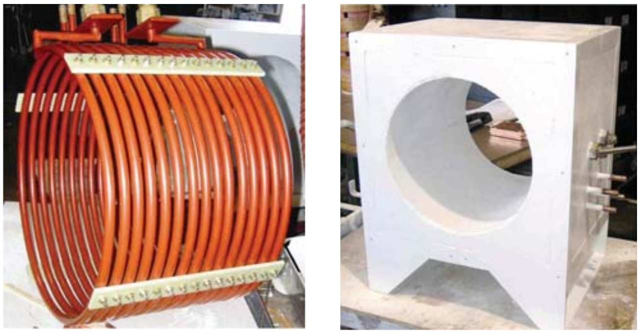

Fig. 2. Examples of multi-turn inductor in as-wound condition (left) and in as-cast condition

Intricacies of Induction Heating of Pipe Ends

Induction heating for stress relieving pipe ends is generally accomplished by placing the end of the pipe in a multi-turn induction coil (Fig. 2), where it statically heats for a specified amount of time.[2] Customers typically specify production rate, final target temperature, required heated length (RHL) at the pipe end, allowable radial and longitudinal temperature deviations, delta T ($\pm\Delta T_R$ and $\pm\Delta T_L$), and the length of the hot-to-cold transition zone. Some applications call for a sharp axial transition zone while others require certain longitudinal temperature profiles.

In stress relieving of oil country tubular-steel goods, the typical temperature-uniformity requirement is ±50°F at target temperature levels of 700-1250°F depending upon the particular steel grade and application specifics. The uniformity achieved in most induction systems is ±80°F, however, when heating a variety of pipe sizes, in some instances heat non-uniformity may exceed ±110°F.

Over the years, a number of induction-coil design concepts have been developed utilizing various process recipes. Manufacturers of induction pipe-end heating machines utilize a wide range of frequencies from line frequency, 60Hz, to 10kHz.

An optimal coil design (including coil configuration, refractory thickness, frequency selection, etc.) corresponds to particular tube size, geometry and material. By selecting a proper combination of coil design and frequency, it is possible to provide needed temperature uniformity along the RHL at the pipe end, but it is practically impossible to have an optimal inductor for every size and geometry of pipe end in the inventory of a connection manufacturer. The need for flexibility is essential.

Electromagnetic End Effects

Temperature distribution within the pipe end is affected, among other factors, by the electromagnetic end effect,[2] which represents a distortion of the electromagnetic field in the end of the pipe (so-called "hot" end) and the end of the induction coil (Fig. 3). End effect can manifest itself as under-heating or overheating of pipe-end area (Fig. 4). As described in reference 2, the electromagnetic end effect is a complex function of several variables, including physical properties of heated material, frequency (F), coil overhang (σ), "coil-to-part" coupling (C), space factor of coil turns and others.

Higher frequency and larger coil overhang lead to a power surplus in the pipe-end area, resulting in a noticeable overheating. In contrast, low frequencies and larger "coil-to-pipe" radial gaps (reduced electromagnetic coupling) will cause a power deficit at the end of the pipe, which will therefore be under-heated.

It is important to realize that a uniform power-density (heat-source) distribution along the end area of the pipe will not correspond to a uniform temperature profile because of the additional heat losses – due to thermal radiation and convection – at the pipe's end area compared to its central region. Proper choice of design parameters makes it possible. The additional heat losses at the end of the pipe are compensated by the additional power (power surplus) due to the electromagnetic end effect. This results in a reasonably uniform temperature distribution within the RHL of the pipe end.

The end effect that appeared when heating ends of the magnetic pipes has several features compared to heating the non-magnetic ones. As discussed in reference 2, magnetic materials have a tendency to gather the magnetic-flux lines because of magnetic permeability. The electromagnetic end effect in a ferromagnetic pipe is primarily affected by two factors.[2]

- The demagnetizing effect of eddy currents, which tend to force the magnetic field out of the workpiece.
- The magnetizing effect of the surface and volumetric currents, which have a tendency to gather the magnetic field within the workpiece.

The first factor causes an increase in power at the pipe's end (similar to the end effect of a non-magnetic pipe). The second factor causes a power reduction there. Therefore, unlike those of non-magnetic materials, the ends of the ferromagnetic pipes have greater tendency to be under-heated, particularly when using lower frequencies and power densities. The results of computer modeling shown in Figure 3 reveals that regardless of a considerable coil overhang of 3 inches (75mm) when heating carbon-steel pipes of 8 inches (203mm) in diameter and 1 inch (25mm) wall below Curie temperature utilizing line frequency (60Hz), the pipe end will be dramatically under-heated due to an appreciable deficit of heat sources within the end area. "Coil-to-pipe" radial gap was 1 inch (25mm).

Bell-shape temperature profiles are quite typical when using traditional, 60Hz, inductors for heating magnetic pipes below the Curie temperature (Fig. 5 top).

In order to provide the required longitudinal temperature uniformity along the end area of the particular pipe, it would be necessary to use multilayer windings in the coil-end areas compared to single-layer windings in its central region and/or fabricate coils with tighter windings of turns near the pipe-end areas versus windings at its central region. As expected, both approaches fell short in providing flexibility. A necessity of having large coil overhangs combined with lower frequencies results in a reduction of coil electrical efficiency and power factor.

Equipment flexibility is extremely important because most customers prefer utilizing a single induction coil or having a minimum number of coil sets for heating a wide variety of different pipe sizes – various diameters, wall thicknesses, heated lengths, etc.

A variety of thermal patterns with appreciably non-uniform longitudinal temperature profiles are produced when lower-frequency, conventional coil designs are used for heating different size pipes. It is typical for such systems to have limited controllability of electromagnetic end effect, resulting in heat non-uniformity.

Call for Higher Frequencies

The use of higher frequencies represents another attempt to improve longitudinal temperature uniformity at the pipe-end area. In the past, there have been a number of successful induction pipe-heating systems – utilizing frequencies in the range of 1-10kHz – supplied to industry. Recent trends to increase pipe wall thicknesses in combination with tighter requirements for heat uniformity, however, have outlined several drawbacks of using higher frequencies versus line frequency when heating thick-wall magnetic pipes to temperatures suitable for stress relieving. These are as follows:

1. As can be seen from Figure 3, when heating thick-wall pipes (even at line frequency) the "skin" effect is very pronounced and the ratio of "wall thickness to eddy current penetration depth" is quite large. Higher frequencies have a tendency to further increase this ratio.[2,3] For example, this ratio can easily exceed 15 when heating thick-wall pipes utilizing a frequency of 1kHz. With 10kHz this ratio can exceed 40. Therefore, there will be a danger of localized overheating the outside surface of thick-wall magnetic pipes while trying to provide a uniform radial temperature distribution. This could result in an undesirable heterogeneous stress-relieving structure.
2. Higher frequencies are noticeably more sensitive to pipe positioning inside the induction coil, meaning that even slight variation in coil overhang could lead to an appreciable tem-

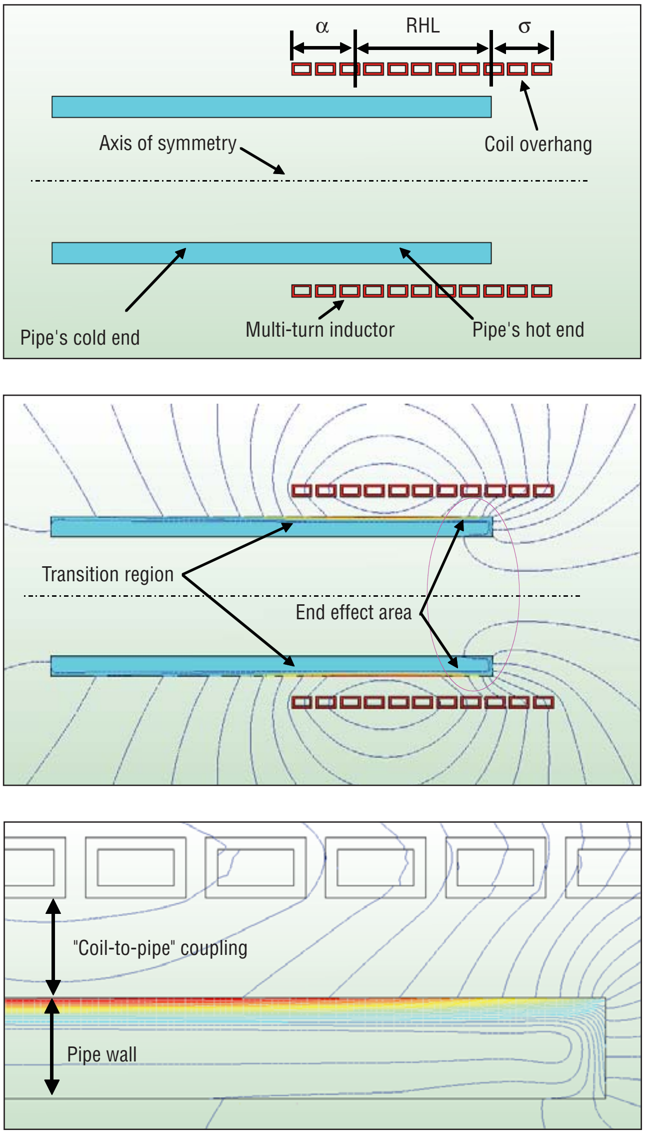

Fig. 3. Sketch of induction heating system (top), electromagnetic field around it (middle) and zoomed view of pipe end effect and skin effect (bottom) obtained after computer modeling

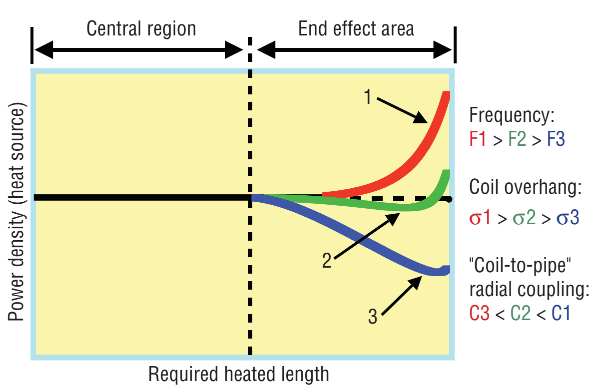

Fig. 4. End effect appearance vs. frequency, coil overhang and "coil-to-pipe" coupling (radial gap)

perature variation at the pipe-end area. This lowers process repeatability and negatively affects controllability of such important electromagnetic phenomena as end effect and proximity effect.[2] Difficulty in controlling electromagnetic proximity effect typically results in the appearance of localized "hot" and "cold" spots (Figure 5, bottom), which appear when the pipe is not positioned symmetrically (radially) within the induction coil. This is very common when various diameter pipes are heated in the same inductor.

3. Higher frequencies are "less forgiving" for having variations of "coil-to-pipe" coupling, which is also the case when heating different size pipes as well as different tapered connections (pin and box-type tapered ends).
4. High frequencies require using solid-state inverters that in some cases could appreciably increase the capital cost of the machinery.

Some commercial applications of high-frequency systems attempt to balance their non-uniform end effects by utilizing a Faraday ring effect. According to this effect, a water-cooled copper ring is located in close proximity to the end of the induction coil. The copper ring "robs" power concentration at the pipe end and is often called a "robber" ring.

An alternating coil current produces an alternating (changing) magnetic field. This field will have the same frequency as the coil current. The changing magnetic field induces eddy currents in the pipe and in other electrically conductive objects that are located near the coil, including a copper ring. Induced currents have the same frequency as the coil current. However, their direction is opposite that of the coil current. Copper-ring current produces its own magnetic field, which has opposite direction to the main magnetic field of the coil. By locating a robber ring in close proximity to the pipe end, a cancellation or noticeable reduction ("robbing" effect) of the main field can be achieved.

Unfortunately, application of a robber ring is associated with additional power losses that add no value to the end product. This additional energy cost is compounded because not only is it not transmitted to the work, but it must also be dissipated as waste thermal load on the cooling system, which is then eventually exhausted into the atmosphere. These are unrecoverable costs that translate into wasted dollars when considering that a machine will run thousands of cycles per year. Since a robber-ring approach relies on using high frequency, it is not free of the aforementioned drawbacks typical for using frequencies of 1kHz and higher. This approach is very sensitive to the robber positioning in respect to induction coil and pipe end as well as the pipe diameter.

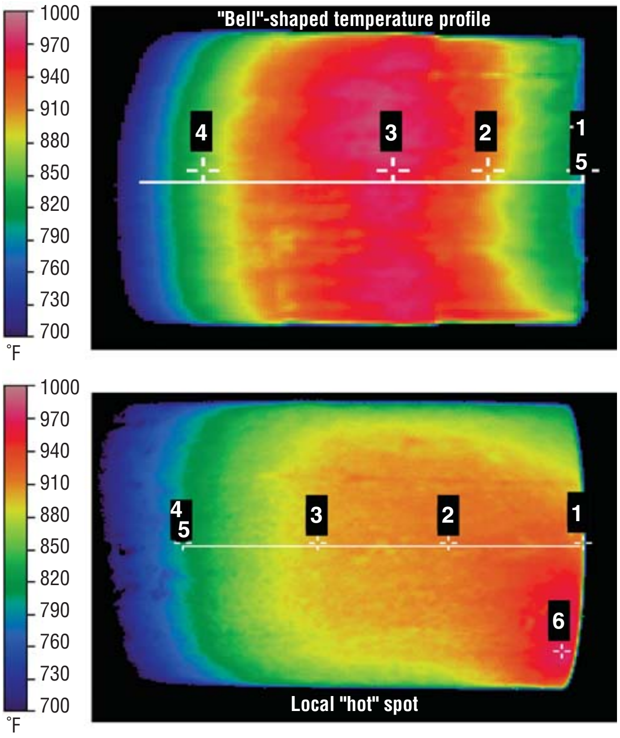

Fig. 5. Thermal images of heated end of steel pipe 11" (280mm) diameter, 1/2" (12.7mm) wall utilizing conventional induction-heating systems

FluxManager™ – Novel Patented Technology

FluxManager™ is a patented technology recently developed by Inductoheat, Inc.[4] Instead of using a robbing effect, it utilizes a "complementing" effect, which appreciably improves shortcomings of existing stress-relieving processes that depend upon using frequencies of 1kHz and higher. It also eliminates the conventional-system drawbacks of under-heated ends when using line frequency (60Hz). Advantages were achieved in the following ways:

- Superior radial and longitudinal temperature uniformity
- Improved flexibility and robustness
- Significant reduction of a probability to overheat surface while heating thick-wall pipes
- Increased production rate and less energy consumption
- Dramatic reduction of an external magnetic field around induction coil
- Total cost reduction

As an example, Figure 6 shows the thermal image of the heated end of a 7.625-inch (194mm) diameter and 0.75-inch (19mm) wall steel pipe utilizing FluxManager technology. Required heated length is 15 inches (381mm), and heat time is 93 seconds. Coil power is about 100kW/60Hz and ΔT=±30˚F.

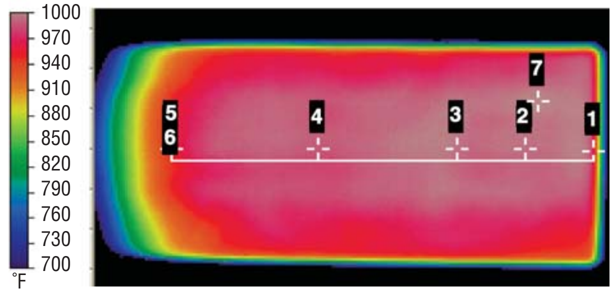

Fig. 6. Thermal image of heated end of steel pipe 7-5/8" (194mm) diameter, 3/4" (19mm) wall utilizing FluxManager™ technology. Required heated length is 15" (381mm). Heat time - 93 sec. Coil power is about 100kW/60Hz. ΔT = ±30˚F

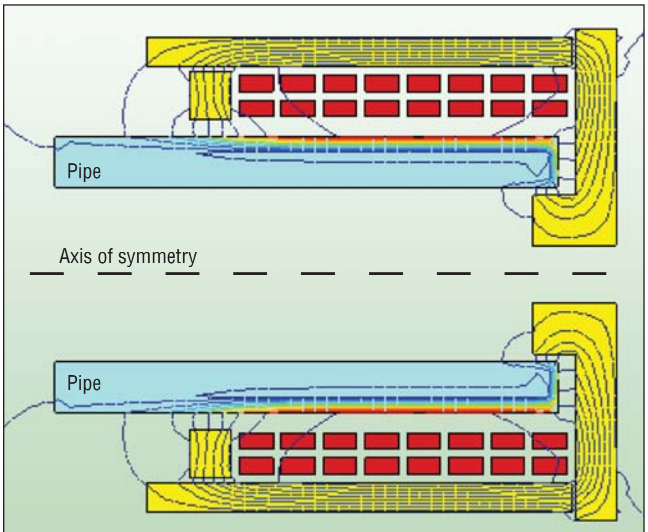

Fig. 7. Computer modeling demonstrates one example of the FluxManager™ concept (magnetic-field distribution)

Unlike other induction-heating systems, the recently patented FluxManager concept[4] utilizes a uniquely designed flux concentrator[2,4,5] that boosts power density at the end of the pipe. This can be adjusted to accommodate different pipe diameters, walls and/or the pin-and-box geometry, resulting in superior flexibility and temperature uniformity at the pipe end (Fig. 7).

Another unique feature of FluxManager is that coil overhang is minimized, providing greater efficiency across the heated length along with adjustable heated length to suit the requirements of the desired stress-relieving application. The transition zone – the area at the back of the heated length above the swage – exhibits a steep temperature gradient, which is evidence that the energy consumed is focused at the work area and is applied only where it is required. If required, the length of the transition zone can be easily adjusted.

Due to a space limitation, it is difficult to discuss the majority of the features of this novel technology. Interested readers are welcome to contact the authors at Inductoheat, Inc. **IH**

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