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An Experimental Evaluation of the Temperature Profiles in Super Duplex Pipe Subjected to Induction Heating and Bending

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This article briefly explains the technique of induction heating as applied to thick-walled super duplex pipe. It describes the theoretical temperature distribution which might be expected through the wall of such a pipe. An experiment is outlined that uses thermocouples to determine the actual temperature profiles within the wall of induction-heated pipe. The results of the experiment are given, and identifiable trends are discussed. A second experiment is then performed where the pipe is subjected to induction bending, and again the results are explained and discussed. Apparent discrepancies between theoretical and actual temperature profiles are then explained.

Keywords induction bending, induction heating, super duplex, temperature profile, thermocouple testing

1. Background

Induction bending is a cost-effective means of making complex, high-pressure pipework; however, the process can produce unwanted changes in pipe geometry such as wall thinning at the extrados, wall thickening and wrinkling at the intrados, and steep transitions in wall thickness between tangent and bend. These problems increase in severity as the bend radius is brought below 2.5 × nominal pipe diameter (Ref 1). Induction bending of thick-walled super duplex pipe requires the pipe to be heated over a very short length to around 1130 °C. At this temperature, the yield strength of the pipe will be reduced to around 10% of the value exhibited at room temperature (Ref 2, 3). The sizable reduction in yield strength of the material at the heated zone ensures that bending is concentrated at that region (Ref 1, 4).

Attempts made to model these geometric changes using elastic-plastic FEA have met with limited success. The authors consider that a key reason for the existing models (Ref 5-7) not agreeing significantly with experimental results (Ref 1) is that the material properties used in previous FE analyses do not accurately reflect those exhibited by the pipe during induction bending. Since Proof Stress (PS) and Ultimate Tensile Stress (UTS) are greatly affected by temperature, the implication is that the temperature profiles suggested by the literature on induction bending (Ref 5, 8) do not reflect reality. Therefore, in this article, the authors have set out to determine the true temperature distribution along, around, and through thick-walled super duplex pipe when it was subjected to induction heating and bending. To this end, an experiment was devised whereby thermocouples could be used to monitor the temperature at various depths through the wall of a thick pipe as induction heating progressed. A second experiment was also conducted where the same pipe still equipped with thermocouples was subjected to induction bending.

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2. Theoretical Temperature Profile Through Thick-Walled Pipe

There are many factors which influence the temperature profile of thick-walled super duplex pipe when it is subjected to induction heating. These factors are; surface heating effect, variations in temperature dependant physical properties of the workpiece, and practical process considerations.

2.1 Surface Heating Effect

When the induction coil is first switched on, eddy currents are at their most intense levels just below the surface of the workpiece with the concentration of the eddy currents dropping rapidly through the wall section. The highest temperatures, and the most rapid temperature rises, should therefore be experienced at, or just below the surface. In order to quantify this phenomenon, researchers refer to the "skin depth" or "penetration depth, δ," which is defined as the layer within which 86% of the heating takes place (Ref 9). The size of the skin depth is dependent on

- *Resistivity* of the workpiece material—the lower the resistivity, the thinner the skin.
- *Current flow* in the induction coil—the higher the current flow, the thicker the skin.
- *Frequency* of the ac current in the induction coil—higher frequencies lead to thinner skins.
- *Magnetic permeability* of the workpiece—the greater the magnetic permeability, the thinner the skin (Ref 10).

In thick-walled pipe, the skin depth may be less than the pipe's wall thickness. Here, complete heating through the wall section of the pipe will depend on the conduction of heat from the material within the skin depth toward the bore of the pipe. In materials with poor thermal conductivity, such as duplex stainless steel, care is required to ensure that the pipe is fully heated (Ref 9).

2.2 Variations of Temperature-Dependant Physical Properties

In ferromagnetic materials, several properties vary with temperature, which include magnetic permeability which is unity above the Curie Temperature (Ref 8), electrical resistance which increases as temperature increases (Ref 8), thermal conductivity which will drop as the temperature rises (Ref 8), and the specific heat capacity which will be at its greatest around the Curie Temperature (Ref 11). Differences in these properties impact the temperature profile, and because none of the properties varies linearly with temperature, their combined effect can be hard to predict.

2.3 Process Considerations

2.3.1 Proximity of the Heating Coil. Because the density of flux lines is the highest near to the surface of the induction coil, it is important that the coil be in close proximity to the pipe. This ensures rapid heating and optimal process efficiency. Holding the coil close to the pipe has the effect of constraining the length of the heated zone, and providing it with more clearly defined boundaries, which in turn focuses the bending point.

2.3.2 Active Cooling. In induction bending it is necessary to cool the workpiece as it leaves the induction zone to ensure that the heated length is kept as short as possible. This is normally achieved by directing a water cooling jet onto the workpiece after it has passed through the induction coil (Ref 9). Backwash of cooling water onto the heated zone is prevented by setting the induction coil and cooling spray a little distance apart, and by using a continuous, and forceful jet of compressed air to blow the water away from the induction coil.

2.3.3 Passive Heat Loss. In areas not affected by the water jet the workpiece will experience passive cooling; convection from the outer surface, conduction along the pipe, and radiation from the inner and outer surfaces. Where the workpiece has a surface temperature above 350 °C, radiation accounts for a greater proportion of the heat loss than convection (Ref 9).

2.3.4 Workpiece Features. During induction heating discontinuities in surface geometry such as projections, slots and holes will heat up more quickly than the main part of the workpiece (Ref 9).

Induction bending of thick-walled pipe requires a few refinements to the normal induction heating process. In induction bending the coil sits eccentric to the pipe, the coil being closer to the pipe's intrados than its extrados. This is done to maximize the temperature, and therefore minimize the yield strength of the material at the portion of the pipe which will be subjected to the greatest geometric deformation. The greater concentration of flux lines near the intrados means that it will heat up more rapidly and will reach a higher temperature than the extrados. In induction bending the coil is switched on and the pipe allowed to heat for a couple of minutes before the bending process begins. This means that the temperature profile through the pipe wall will be fully developed before bending starts. As, the pipe moves slowly and continuously through a stationary coil, we can thus expect some pre-heating of any given section of the pipe by conduction before that section reaches the induction coil.

In order to summarize, the theoretical, idealized, process cycle would be as follows:

- Initial heating by conduction along the pipe from the heated zone
- Rapid heating of the surface of the pipe as it enters the induction zone
- Increase in the depth of the heated zone. The temperature at the outer surface will be higher, and will remain higher, than any other point through the wall section
- Outer surface attains maximum temperature. The maximum temperature through the wall, never matches the temperature of the outer surface.
- Rapid cooling of the outer surface as the pipe encounters the cooling spray.
- Cooling of the pipe material through the wall as heat is conducted from the wall section to the colder outer surface if the cooling is effective, then the pipe should be at the same, much reduced, temperature across the whole wall section, at the point where it leaves the cooling zone.
- Slower cooling of the pipe by conduction, convection, and radiation after it leaves the active cooling zone.

3. Experimental Work

When bending thick-walled super duplex pipe the rig will normally feature a single turn induction coil. Cooling water will be played onto the surface of the pipe by means of radially directed jets. The pipe is moved through the induction coil and cooling jets at a constant feedrate by a hydraulic ram. Pipe temperatures are monitored by optical pyrometers (refer to Fig. 1), and the pipe temperature kept within preset boundaries by varying the magnitude of the alternating current. The ends of the pipe are normally plugged, and the bore filled with an inert gas, typically Argon.

Two types of experiment were conducted. In the first, a length of thick-walled super duplex pipe was fitted with thermocouples and fed through an induction coil and cooling spray. Here, the pipe was heated but not bent. The nature of the set up and methodology meant that the experiment could be repeated several times. In the second type of experiment, this same pipe was subjected to induction bending. During induction bending, the test pipe was permanently deformed, and so this experiment could be performed only once.

3.1 Experimental Configuration

A straight piece of super duplex pipe conforming to UNS S32760 of 6.625″ (168.1 mm) OD × 25.4-mm wall thickness was drilled with a series of holes along and around the pipe to a variety of depths (refer Fig. 2). Each hole was populated with a thermocouple, and the thermocouple secured with thermal cement. The thermocouples were connected to a dataTaker™ DT500 data logger which was set to sample with maximum rapidity, this resulting in a schedule time of 1.3 s. The data were saved to an Excel™ spreadsheet. The induction bending rig was set up as it would be if the pipe were to be bent; the same coil was employed, the coil was offset in the usual

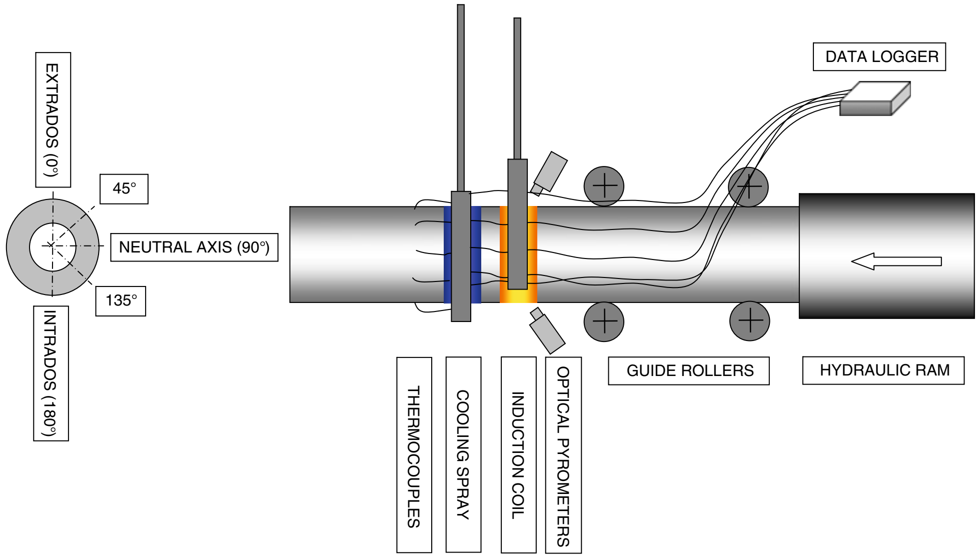


Fig. 1 Induction heating rig including experimental set up

manner—closer to the pipe's intrados than its extrados, the frequency and magnitude of the alternating current in the induction coil were the same as if bending were taking place, i.e., 650 A and 780 Hz respectively. The cooling ring was supplied with water at 3 °C. Compressed air, at a temperature of 2 °C, was directed through the induction coil and toward the cooling water to keep it from impinging on the heated zone. The induction coil and cooling spray were turned on and the heating zone brought up to 1130 °C at the intrados and 1070 °C at the extrados, as measured by dedicated Ircon 3R99C05 optical pyrometers The heated zone was allowed to stabilize, before the pipe was moved forward at 35.1 mm/min. The only way in which the experimental process differed from the normal bending process was that, in the first diet of experiments, the bending arm of the machine was not connected to the pipe. Thus, the pipe was heated and moved forward, but was not bent (refer to Fig. 3). Multiple repetitions were performed.

The second experimental type used exactly the same setup as the first, except that in this instance the machine's bending arm was connected in such a manner as to produce a bend with radius of $2\times$ nominal pipe diameter, i.e., 305 mm. The arc angle of the bend was chosen as 114° to guarantee that all of the thermocouples were included within the main part of the bend away from the transition regions (refer to Fig. 3). The geometry of the pipe was such that the thermocouples had to be distributed along the pipe when ideally they would all have occupied the same plane. However, due to the feed rate of the pipe, the position of the thermocouples and the frequency of readings (which were known and constant), it was possible to correctly align the data by making an appropriate temporal adjustment within Excel™. On the extrados, a double set of thermocouples was used to allow the constancy of the heating process to be assessed. Multiple runs were performed to verify the repeatability of the process.

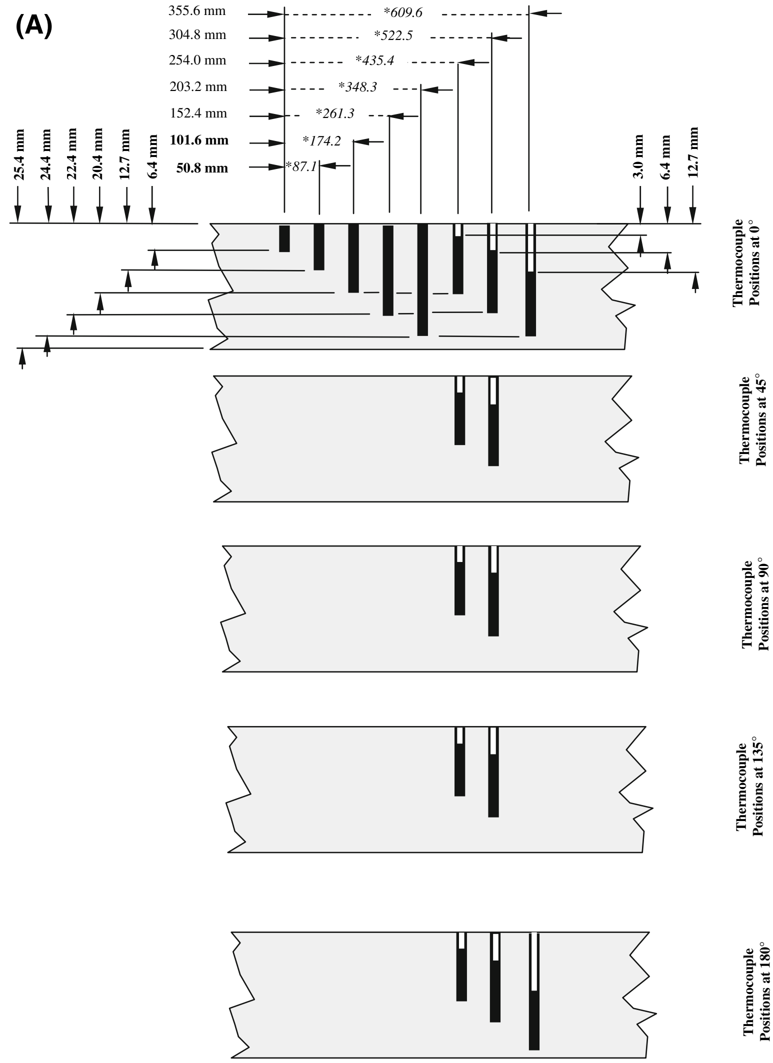
3.2 Experimental Challenges

The authors faced three main challenges when designing the experiments. The first was sourcing thermocouples which would survive the high temperatures expected and would provide accurate, sensitive data. The second was ensuring that the act of placing the thermocouples within the pipe would not result in spurious readings. The third was ensuring that enough thermocouples survived the forces inherent in induction bending, caused by material movement, to provide a good spread of data.

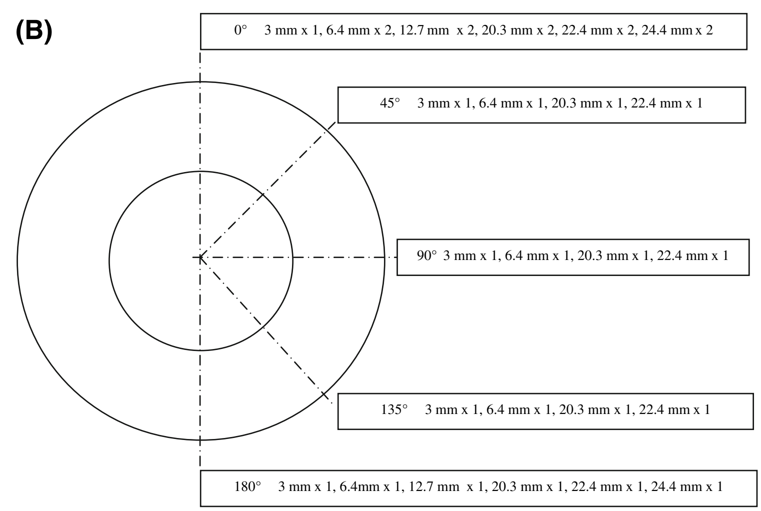
The first issue was solved by having thermocouples custom made to fit the projected parameters. The second issue manifested itself in two forms; that the holes drilled into the pipe might disrupt the magnetic flux in such a way as to cause localized over-heating of the material immediately around the holes (Ref 9), and that the material of the thermocouples would be differentially heated by the process of induction heating. The literature suggests that, to avoid over-heating, holes can be temporarily filled with metallic plugs (Ref 9). It was decided, therefore, to make the dimension of the holes in such a way that the inside diameter of the hole would be a very close match to the outside diameter of the thermocouple. This allowed the thermocouple to act as the metallic plugs while simultaneously guaranteeing good thermal contact between thermocouples and pipe material. The second concern could only be addressed by critically viewing the experimental data and assessing whether the thermocouples which provide accurate data. The third issue was addressed by choosing a bend radius which was a compromise between providing a large enough change in pipe wall thickness (and related geometric changes) and not producing material movements so large as to lead to the destruction of the thermocouples. The compromise ($2\times$ nominal pipe diameter) was within the range of bends considered to be tight (below $2.5\times$ nominal pipe diameter) but less than the very tightest bend previously produced by the same authors (Ref 1).

4. Results

Despite concerns about the thermocouples' robustness, they performed admirably, most of the thermocouples



Number of thermocouples at particular linear displacements.
* Temporal displacements given in seconds – these assume that the pipe moved at 35.1 mm/min.



Number of thermocouples at particular angular displacements

Fig. 2 Experimental setup showing location of thermocouples

Fig. 3 Experimental setup for linear and bend testing

survived the first diet of experiments and an acceptable number survived induction bending. During both induction heating and induction bending, general agreement was observed between the readings of maximum temperature obtained from the thermocouples near the surface of the outer diameter of the pipe and the readings obtained from the optical pyrometers (the former recording a maximum extrados temperature of 1031 °C, and the latter 1043 °C). In addition, the width of the heated zone during induction heating tests, as determined by the extrados thermocouples (based on time that the 3.0-mm extrados thermocouple experienced temperatures above 940 °C, the temperature at which steel turns orange), bore a close resemblance to the width of the heated zone as estimated by the operator (based on the width of the orange and lemon colors on the extrados). The thermocouples suggested a heated zone width of 22.9 mm whereas the operator estimated the zone to be 20 mm wide. No differences in color (and therefore differences in temperature) were seen in the material around the holes. From these observations, the authors draw the following encouraging conclusions:

(a) The thermocouples provided a true representation of the temperatures generated in the pipe. The material of the thermocouples does not appear to have been differentially heated by the induction heating process nor do the holes appear to have caused localized hot spots.
(b) The process shows good constancy; thermocouples placed at the same depth and angular displacement at different points along the pipe showed very similar time/temperature profiles (see Fig. 4).
(c) The process shows good repeatability; individual thermocouples show very similar time/temp profiles in repeated runs (see Fig. 5).

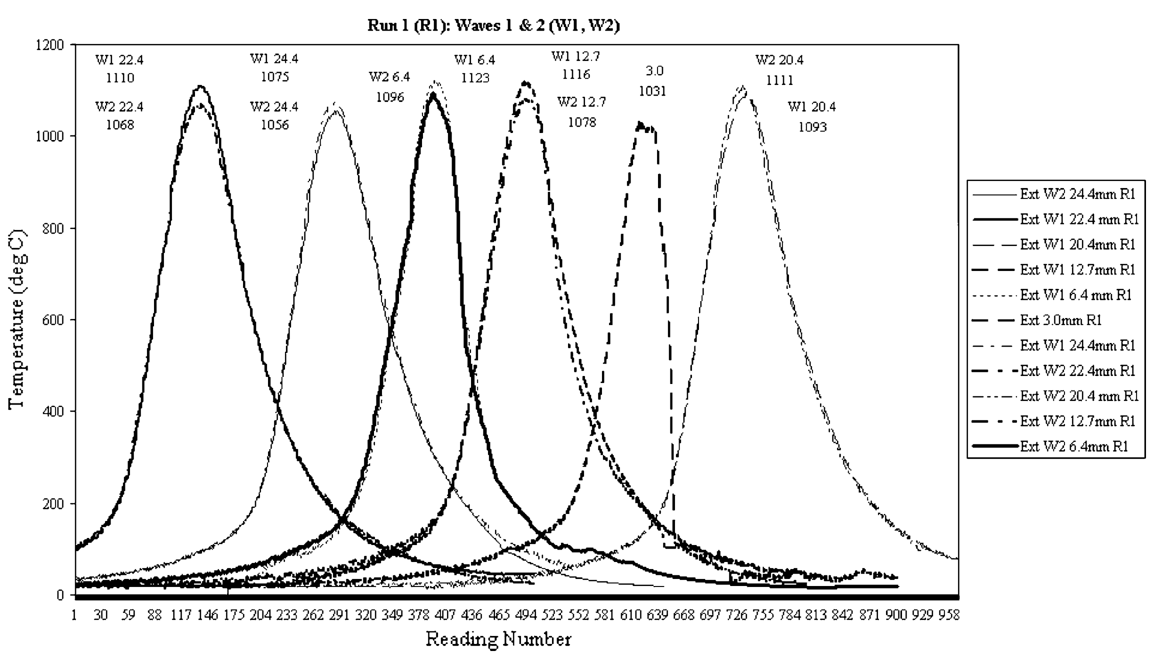


Fig. 4 Time-temperature curves for all extrados thermocouples showing constancy of process

Detailed examination of the data obtained during linear testing allowed the following observations to be made:

1. Thermocouples placed near the outer surface of the extrados of the pipe showed a distinctive conduction heating—induction heating—forced cooling—passive cooling profile (refer to Fig. 6). This same shape can also been seen, albeit to a lesser extent, on all of the extrados thermocouples down to a depth of 22.4 mm (refer to Fig. 6).
2. Thermocouples placed near the outer surface of the pipe heat up faster than those placed deeper in the pipe wall; however they do not attain as high a maximum temperature as those deeper within the wall section (refer to Fig. 7).
3. The highest temperatures tend to be attained by thermocouples part way through the wall section, typically 1110.5 °C at 20.4-mm depth (refer to Fig. 7) and 1123 °C at 6.4-mm depth (refer to Fig. 1).
4. Thermocouples placed near the surface of the pipe attain their maximum temperature earlier than those placed deeper within the pipe; however, they experience their maximum for a shorter time, i.e., a thermocouple placed at 3.0-mm depth typically experienced temperatures

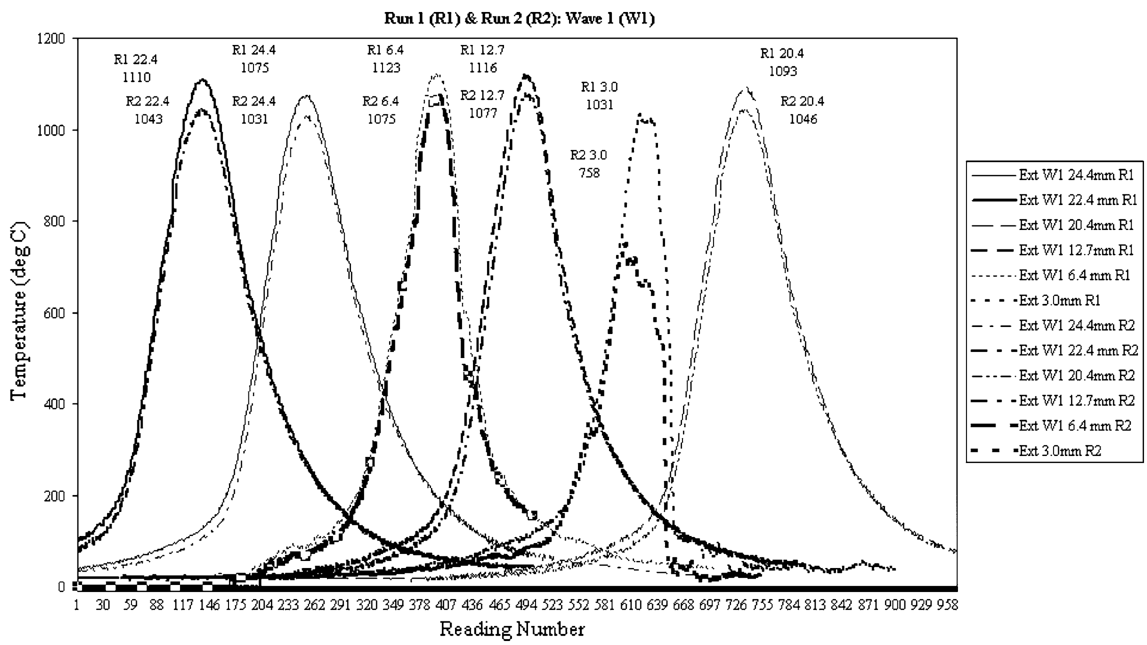


Fig. 5 Time-temperature curves for all extrados thermocouples comparing two runs showing repeatability of process

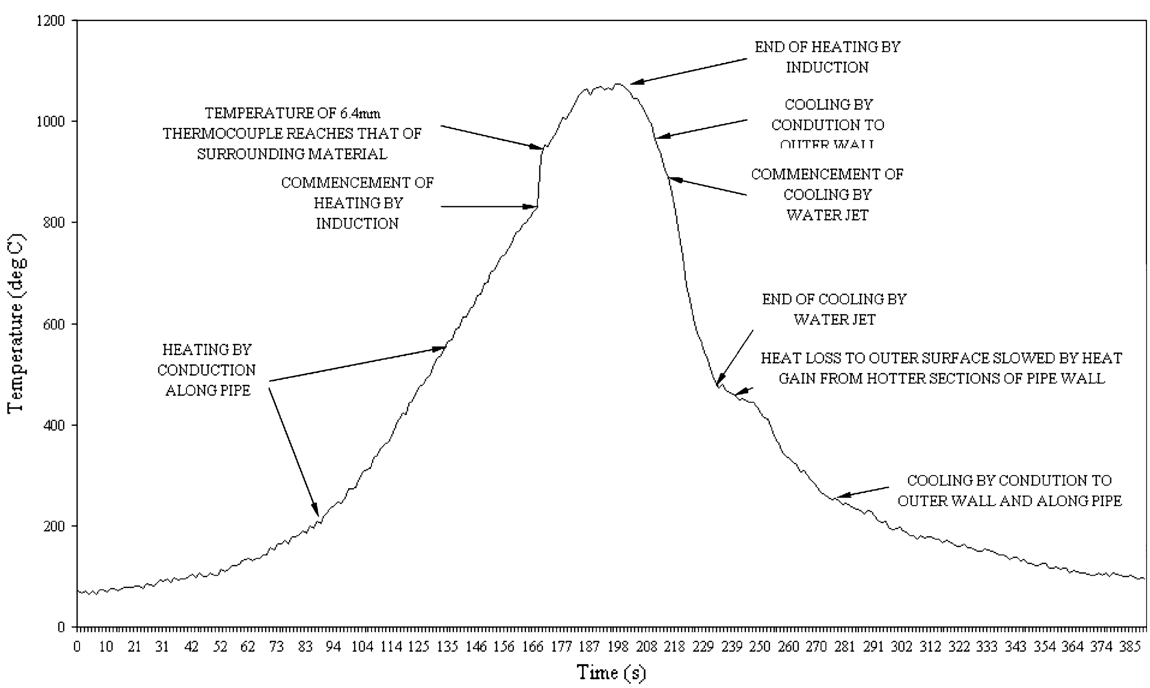


Fig. 6 Thermocouple at 6.4 mm at extrados of pipe showing key features of induction heating and forced cooling

above 800 °C for 53.5 s, whereas a thermocouple placed at 20.4-mm depth experienced temperatures above 800 °C for 92.7 s (refer to Fig. 7).

5. Thermocouples near the surface of the pipe experience the effects of active cooling sooner than those lying deeper; they also cool more rapidly (refer to Fig. 7).
6. The trace from the extrados thermocouples shows a distinctive "notch" just before the commencement of induction heating (refer to Fig. 8). The reason for this is not yet fully understood by the authors. The step increase in temperature displayed by the extrados thermocouples as they enter the induction zone tops out as the thermocouple reaches the same temperature as the hottest material at that particular depth in different angular locations. From this point onward, all of the thermocouples at that depth continue to experience a common rate of temperature rise whatever their angular location might be (refer to Fig. 8).

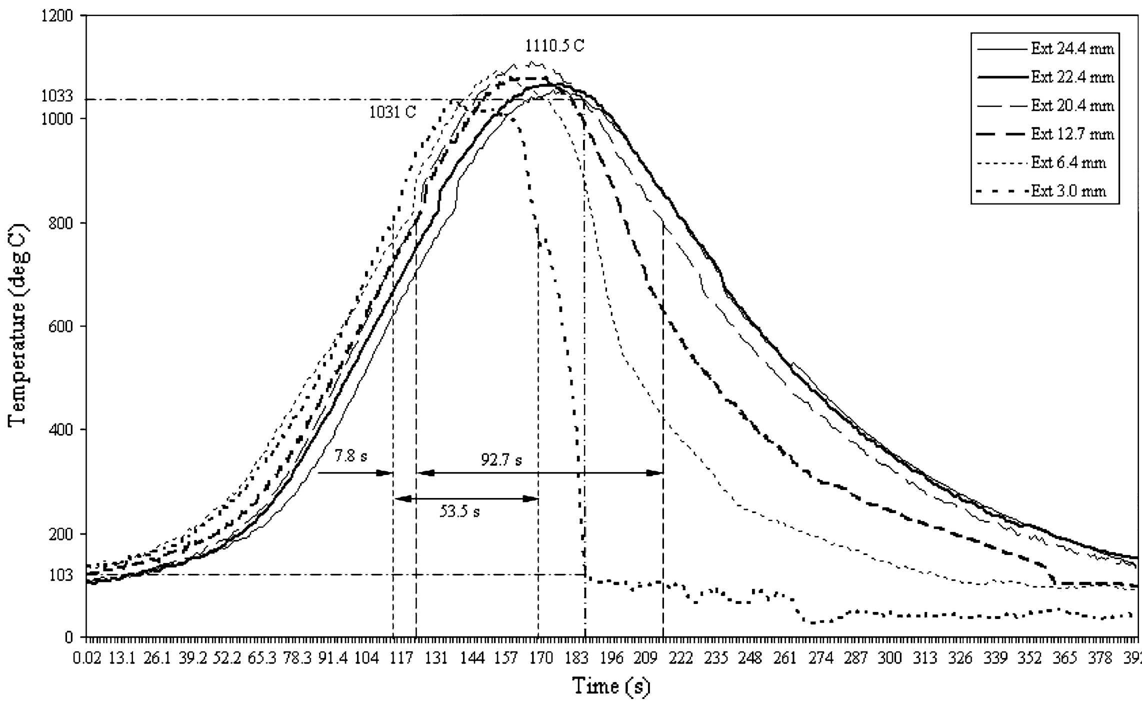


Fig. 7 Thermocouple at extrados of pipe showing variations in of induction heating and forced cooling profiles for different depths

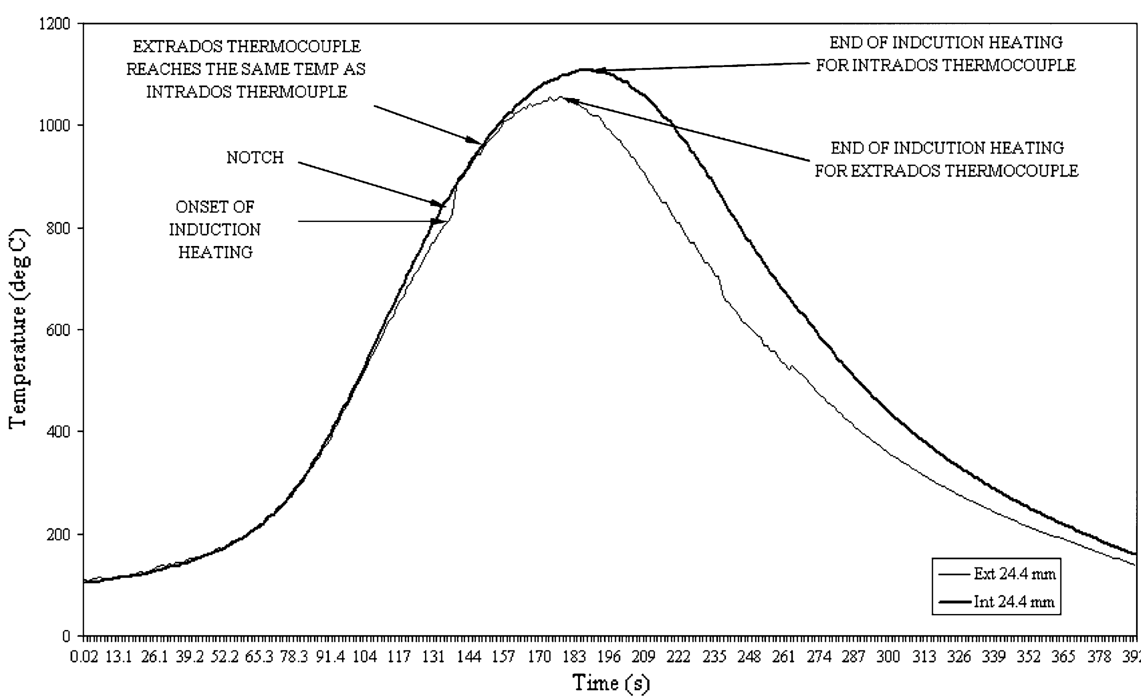


Fig. 8 Comparison of time-temperature profiles for 24.4 mm thermocouples at the intrados and extrados

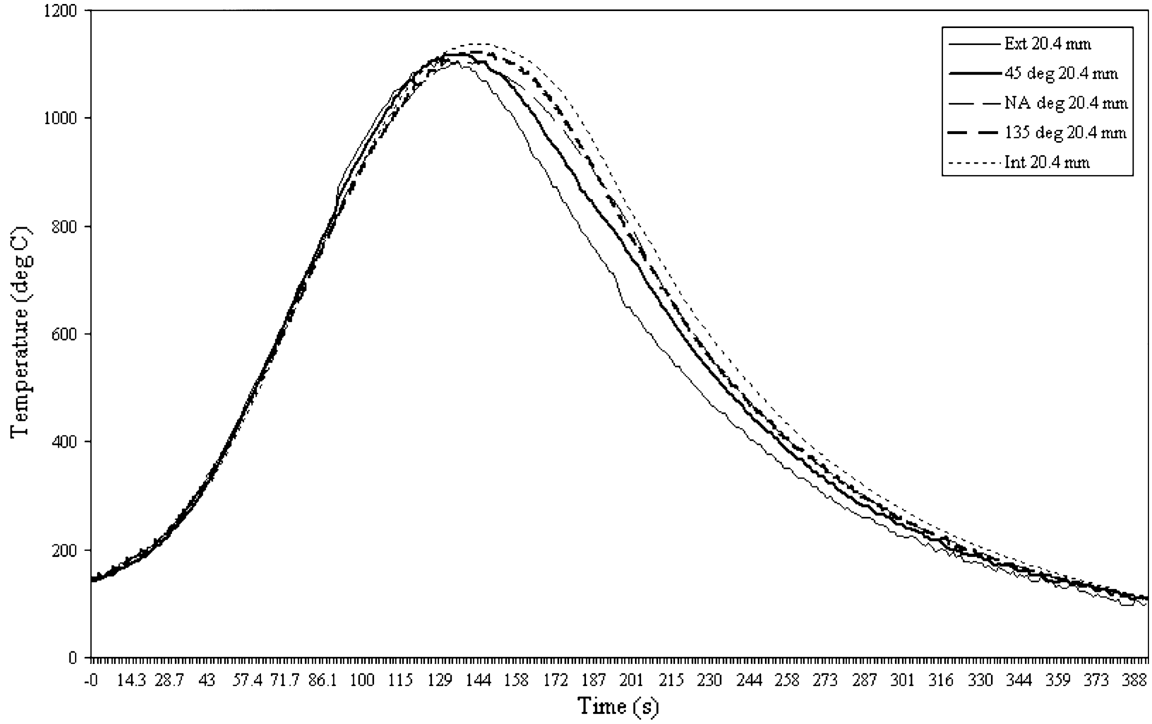


Fig. 9 Comparison of time-temperature profiles for 20.4 mm thermocouples at various angular displacements

7. Thermocouples at the intrados attain higher maximum temperatures than thermocouples at the same depth at other angular positions (refer to Fig. 8).
8. The shorter time at maximum temperature combined with the more rapid cooling of the thermocouples near the surface leads to a situation where at one point in the process, the material at (and just below) the surface is significantly colder than that through the wall section, typically 103 °C at 6.4-mm depth and 1033 °C at 20.4-mm depth (refer to Fig. 7).
9. Comparison of thermocouples located at different angular positions show that thermocouples placed near the outer surface of the intrados of the pipe do not show the well-defined profile displayed by thermocouples set at the same depth at the extrados. At the intrados, the curves are all smoother and rounder, the maximum temperature is higher than that at the extrados, it is achieved later than that of the extrados, and it is maintained for longer than that at the extrados.
10. Cooling appears to be dependent on angular position. Thermocouples at the extrados cool down more rapidly than those further round the pipe (refer to Fig. 9). This is true for all thermocouple depths.
11. There is clear evidence of re-heating, or in less severe cases, a reduction in the rate of cooling, from some of the thermocouples near the surface (refer to Fig. 10).
12. The temperature distribution through the wall section on a radial transect strongly suggests a parabolic form (refer to Fig. 11). This holds true whether the distribution is considered at the extrados, 45°, 90°, 135°, or the intrados. However, the parabolic nature of the temperature distribution is the most apparent at the extrados.
13. If we consider temperature plots through the wall section of the pipe at the extrados, then we find that as we move closer to the induction zone, material nearer the outer surface rises in temperature first, then the material midway through the wall, followed by the material roughly ¾ of the way through. At the point where the mid-section of the pipe reaches its maximum temperature, the thermocouples near the outer surface are already showing marked cooling (refer to Fig. 12).

If we compare the data obtained during induction bending with that observed in the linear testing, then it is apparent that the data from the repeated linear test produced temperature profiles and trends which are indeed representative of what happens during induction bending. In particular, observations 2, 3, 4, 5, 7, 8, 10, 12, and 13 (refer to Fig. 13-15, respectively) for the linear test apply equally to bent and unbent pipes.

5. Comparison of Results with Theory

In the idealized process cycle described earlier, material at or near the outer surface of the pipe starts to heat up earlier, heats up faster, attains a higher maximum temperature, and, at all points in the process, is hotter than material deeper within the wall section. The experimental results show that while material near the surface heats up earlier than the remaining material, it does not reach a higher maximum temperature, nor does it maintain a higher temperature for the complete process cycle. The reason for this is undoubtedly the effect of cooling. Material near the surface will be more affected by losses due to radiation and convection than material deeper in the wall section. When the pipe enters the cooling zone, the water plays directly on the outer surface, and so inevitably it will cool more rapidly; the rest of the material following as heat is lost from

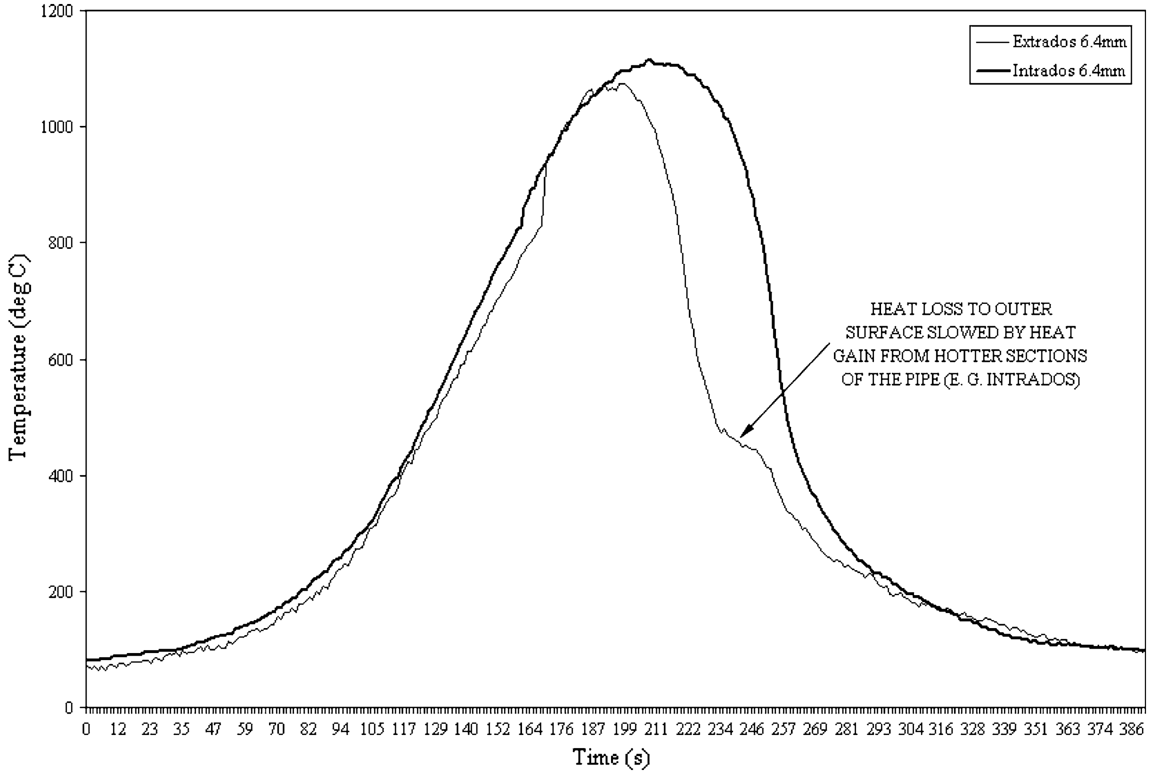


Fig. 10 Comparison of time-temperature profiles for 6.4 mm thermocouples at intrados and extrados showing interruption of cooling at extrados

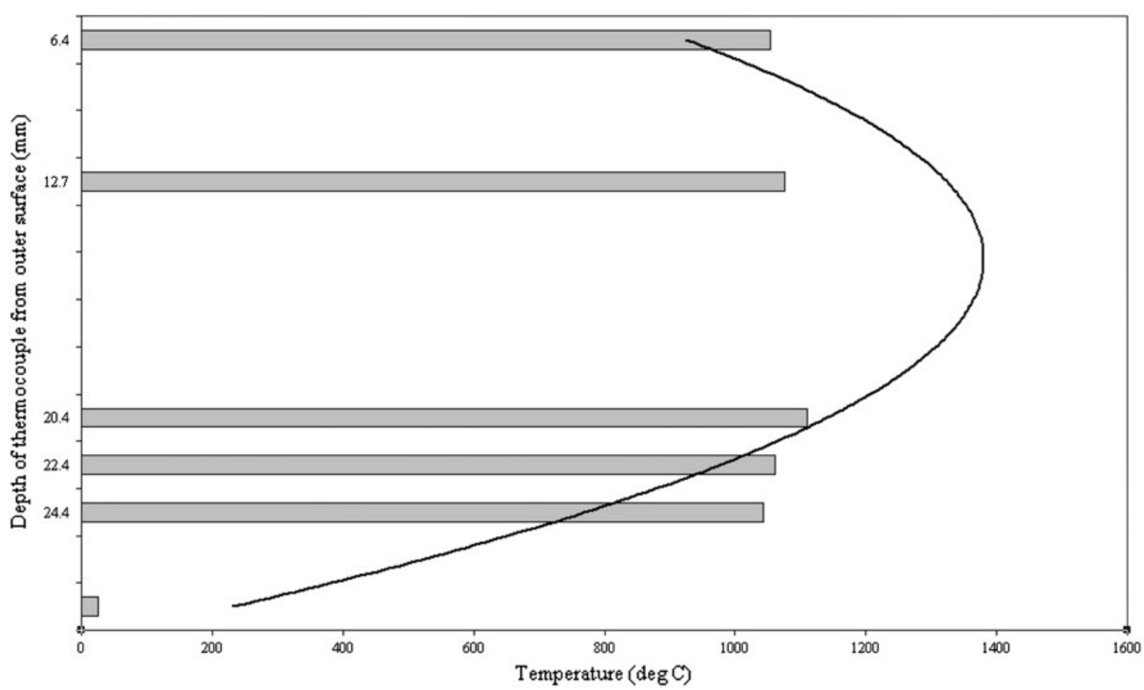


Fig. 11 Temperature distribution across the wall section at the point where maximum temperature is reached

mid-wall to surface. While heat is also lost across the bore surface of the pipe, here, the potential for cooling is much less as the bore is filled with almost stagnant argon, negating any opportunity for convection.

The highest temperatures were consistently found at part of the way through the workpiece. This is partially explained by the rapid loss of heat from the surface of the pipe; however, it also suggests that the penetration depth for this process was

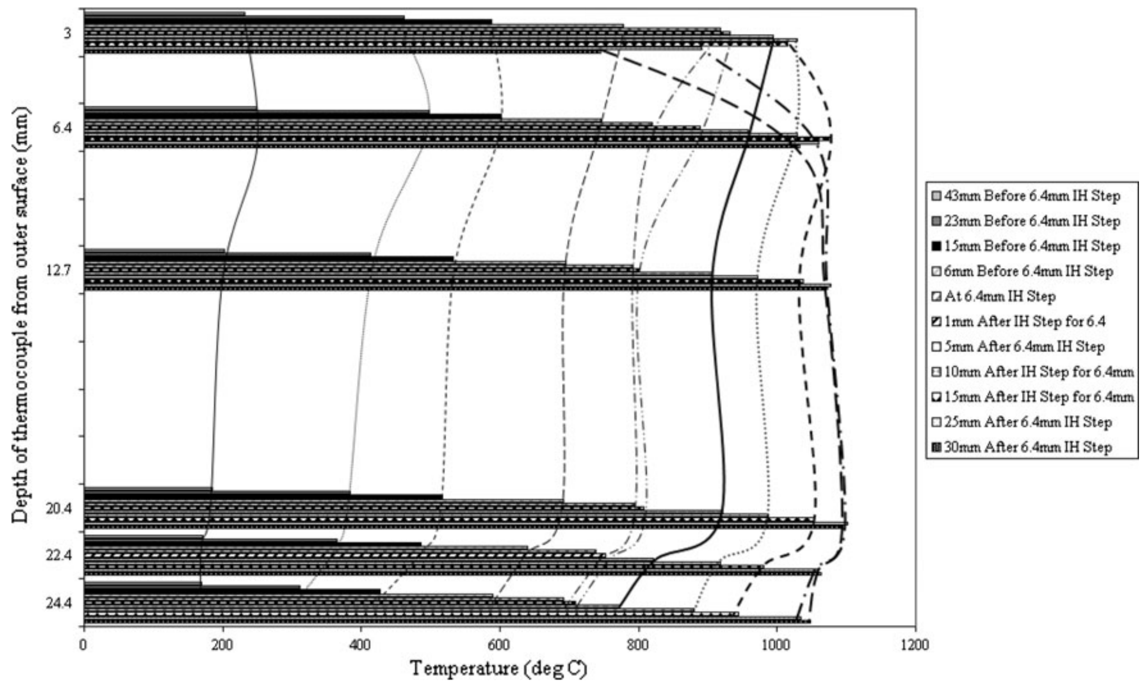


Fig. 12 Temperature profile across the extrados of the pipe at various distances from the induction coil

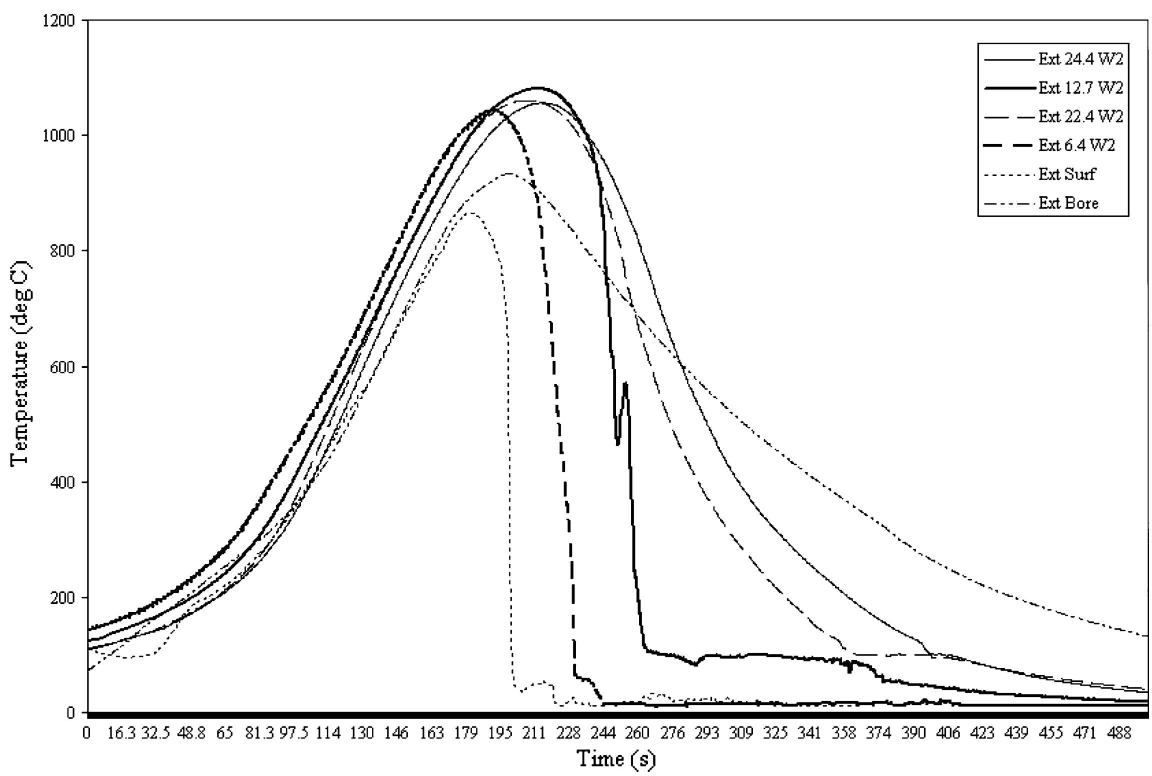


Fig. 13 Time-temperature profiles for thermocouples at a single angular displacement showing variations in of induction heating and forced cooling profiles for different depths during induction bending

somewhere around the location of the 20.4 mm thermocouple. Girish (Ref 12) provides an empirically derived formula for calculating the penetration depth, i.e.,

$$\delta = 80264\left(\frac{\rho}{\mu f}\right)^{1/2}$$

Taking $\rho = 1.125$ μΩm (Ref 11), $\mu = 1$ (as the material is above the Curie Temperature) (Ref 8), and f is the frequency of the current in the induction coil (measured at 780 Hz), we obtain $\delta = 19.9$ mm. The penetration depth estimated by scrutiny of the thermocouple data does, therefore, seem to agree with the calculated penetration depth.

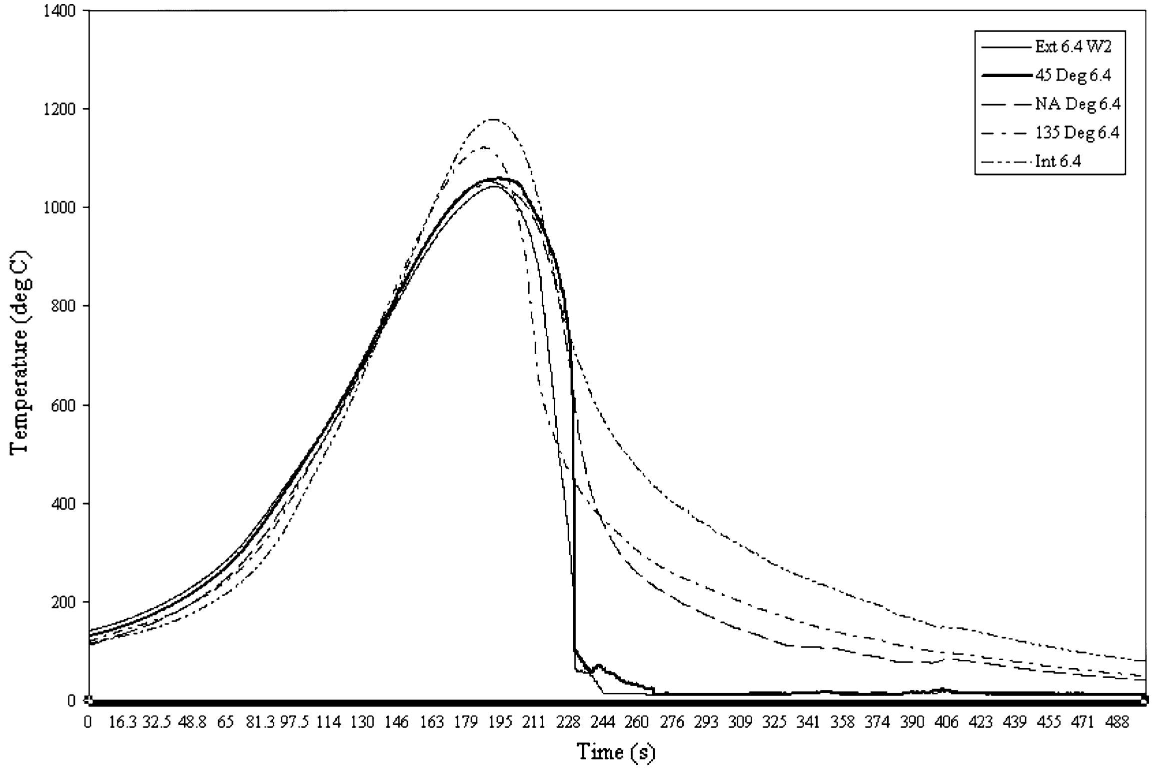


Fig. 14 Comparison of time-temperature profiles for 6.4 mm thermocouples at various angular displacements during induction bending

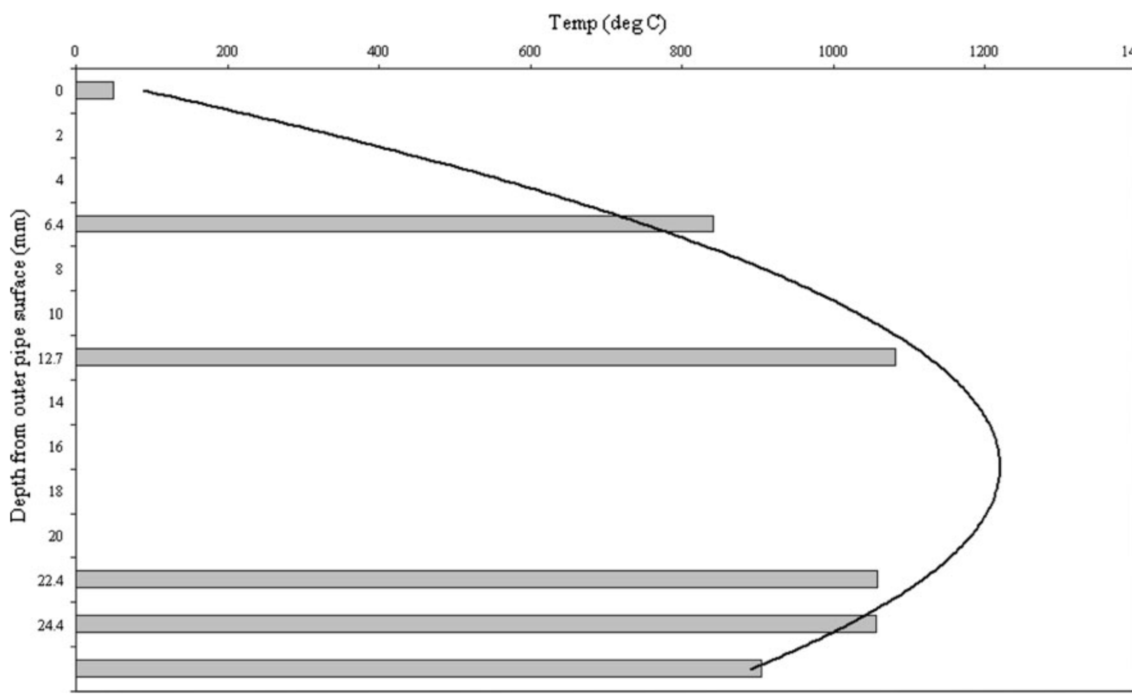


Fig. 15 Temperature distribution across the wall section during bending at the point where maximum temperature is reached

Material deeper than the penetration depth is assumed to have been heated mainly by conduction from the hotter parts of the pipe than by direct induction heating. Taken together the rapid heat loss from the outer surface, the lower heat loss to the bore, and the drop in efficiency of induction heating for depths greater than penetration depth would explain the parabolic nature of the temperature profile through the wall section seen in Fig. 11 and 15.

The reason that the intrados temperatures are higher than the extrados temperature is the result of the induction coil being offset toward the intrados. This fact may also explain the smoother heat/cool cycle at the intrados. The greater temperature generated at the intrados seems to lead to more heat being conducted along the pipe at the intrados than the extrados. The premise that close-coupling of the induction coil to workpiece will result in a narrower heated zone is contradicted by the evidence. The results presented here show that at the intrados, where close coupling occurred, the heated zone was broader than at the extrados. This apparent anomaly may be explained by the affects of greater conduction of heat, as explained above, and the effects of differential cooling.

Induction heating relies on conduction of heat from parts of the workpeice which are directly heated to those which are not. In the idealized process, this conduction is assumed to occur to and from material encircled by the induction coil. What appears to happen in reality is that a majority of the temperature rise is experienced by the pipe before it enters the induction zone. Theoretically for ferromagnetic material, induction heating occurs partially by eddy current and partly by magnetic hysteresis. However, it is apparent from the thermocouple data that by the time induction heating commences, the material has already exceeded the Curie Temperature, and so magnetic hysteresis plays no part in the heating.

It is apparent that, unlike the idealized process, cooling does not happen instantaneously, nor does it happen evenly across the pipe's wall section. The cooling of the material at the extrados appears to happen more rapidly, and slightly earlier, than at the intrados. The smoother shape of the cooling phase at the intrados may be an anomaly produced by the orientation of the pipe with respect to the cooling water jet. During testing, the pipe was positioned such that the thermocouples at the extrados were at the top, and those of the intrados at the bottom. The cooling water was supplied from a ring which sprays water onto the pipe circumferentially through a series of nozzles on this ring. Owing to the nature of the water flow following impingement on the pipe, the extrados experienced only cold water direct from the nozzles. At the intrados, the cooling water reaching the surface of the pipe is a mixture of cold water from the nozzles and hot water which has flowed from the top of the pipe round the circumference to the bottom. The combined effect of this is a reduced rate of cooling of the pipe at the intrados.

The fact that the time/temperature profiles are so similar for all of the thermocouples at a given depth shows that the rate of heating is depth dependent, and is not influenced by the proximity of the induction coil. The onset of heating seems to be closely related to depth as, when all of the thermocouples from a particular angular location are compared, the order in which heating takes place is from the shallowest to the deepest. This is true irrespective of angular position. Further, since the cooling is neither quick nor comprehensive; this may have a bearing on the metallurgical properties of the pipe, and this may in turn require the pipe to be subjected to post-bend heat treatment (Ref 4). The delay in the heating of the deeper thermocouples combined with the longer duration at elevated temperature means that the material near the bore of the pipe will remain extremely hot (therefore, soft and ductile) for a period after the material near the surface of the pipe has cooled, allowing near-normal mechanical properties to be restored (refer to Fig. 11 and 13). The authors believe that it is this significant difference in mechanical properties which leads to the distinctive geometric deformation seen when thick-walled pipe is bent to very tight radii (Ref 1).

6. Concluding Remarks

During the process of induction bending of thick-walled pipes, the theory of induction heating will not by itself accurately predict the temperature profile through the wall section of the pipe. Conduction of heat along the pipe in advance of induction heating, eccentric positioning of the induction coil, differential cooling from the water jet, differences in rate of heat loss from the inner and outer surfaces, and reheating of cooler regions by hotter regions of the pipe all significantly affect the temperature profile through, along, and around the pipe wall. When modeling the process of induction bending by FEA, it is important that researchers take the effects of the practical aspects of induction heating into account. The authors are confident that the data presented in this article will enable more accurate elastic-plastic FE models to be developed that simulate the induction heating and bending of thick-walled super duplex pipes.

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