

Finite Element Analysis of BWR Welded Pipes

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This paper presents results of finite element analyses of 4-inch and 26-inch diameter BWR welded pipes (type 304 stainless steel) under loads representative of operating and upset conditions. The models included the residual stresses caused by welding as an initial condition. Different residual stress distributions in the weld metal and heat affected zone (HAZ) were considered. Different material properties (yield stresses) were used to model the weld metal, HAZ's and base metal. A 4-inch diameter pipe with Induction Heating Stress Improvement (IHSI) was analyzed and compared to the as-welded pipe. It is concluded that IHSI will provide a definite improvement in the state of stress over as-welded 4-inch diameter pipes. The compressive residual stresses along the inner surface, produced by IHSI, will be slightly reduced if an upset loading occurs, but, during operating loads, residual stresses are unaffected. Furthermore, it would require a very large overload (39ksi) to completely obliterate the beneficial compressive stresses along the ID. The 26-inch diameter as-welded pipe has through-wall axial stresses at operating load that become compressive a short distance from the inner surface which is under tension. This compressive stress prevents the growth of a crack. The situation is different for the 4-inch as-welded pipe, which will be predominantly under tension for the same operating stress. It is concluded that the weld parameters of counter-bore length, weld crown, drop through or suck up have only minor influence on the redistribution of stress. In all cases examined, yielding commences in the pipe at about the level of operating loads, and the pipes would be fully plastic at 136% of yield load.

1. Introduction

Beginning in fall of 1974, a number of cracks were found at the welded junctions of type 304 stainless steel piping systems that are used in boiling water reactor (BWR) nuclear plants. Prior to 1974, isolated cracking incidents had occurred. Cracking was initially observed in small diameter pipes, such as 4-inch diameter recirculation bypass lines. Thereafter, progressively larger and larger pipes experienced cracking. Analysis of these failures [1,2] indicates that cracks were caused by intergranular stress corrosion (IGSCC). Austenitic stainless steels are susceptible to stress corrosion cracking because of microstructural changes known as sensitization which occur during welding. The welding process also generates high tensile residual stresses, particularly in the heat affected zone (HAZ) where many of the cracks occurred.

The object of this work is to investigate the redistribution of stresses in BWR pipe weldments under applied loading conditions when residual stresses are present. Since IGSCC cannot occur in the absence of sustained tensile stresses, the determination of stresses and strains is an important step for the analysis and understanding of stress corrosion cracking phenomena occurring in welded BWR pipes. In this paper, 4-inch and 26-inch diameter welded pipes (type 304 stainless steel) have been analyzed, using the finite element method. The residual stress distribution has been included as an initial condition in the weld metal and the heat affected zone (HAZ). Both as-welded 4-inch and 26-inch diameter pipes and a 4-inch diameter pipe with residual stress improvement by means of induction heating (IHSI) are analyzed. The object of IHSI is to produce compressive residual stresses along the inner surface of the pipe. Compressive stresses prevent crack growth.

2. As-Welded Pipes

2.1 4-Inch Diameter Welded Pipe

Of all the BWR piping systems, the 4-inch diameter (as-welded) pipes have been most extensively studied and documented because cracking was initially discovered in 4-inch piping. Eason, et al. [3] has recently compiled a data base for BWR pipe cracking incidences, which shows that cracking in small lines continues to dominate the problem.

Measurement of residual stresses in 4-inch pipes by General Electric and Argonne National Labs., indicates that stresses are nonaxisymmetric [1, 4]. Also, considerable variation occurs from one weld to another. Instead of analyzing here a pipe with three dimensional state of residual stresses which would require a large computational effort, an axisymmetric state of residual stresses will be analyzed as an approximation. A typical finite element model of a 4-inch diameter welded pipe used in this analysis is shown in Fig.1, where symmetry conditions are implied at the weld center line. 4-Node isoparametric elements were used in the MARC [5] program. Different element properties are used to model the weld metal, the heat affected zone (HAZ), and the base metal (304 stainless steel). The HAZ is subdivided into elements with different properties to reflect the varying yield strengths in the HAZ. The difference in the yield strength in the HAZ is a consequence of the differences in the temperature during welding, cooling rate, and strain experienced within the HAZ during welding. Stress-strain curves were developed for each material type at the operating temperature 550⁰F, based on the results of tension tests on small samples taken from separate regions in the HAZ [6] of a 26-inch diameter pipe. Some recent experimental results by Diaz at General Electric [7] indicate that yield strength in the weld metal and HAZ for a 4-inch diameter pipe are lower than the 26-inch diameter data. Fig. 1 indicates the yield strengths

for 4-inch as-welded and IHSI pipes. The strain hardening slope is assumed to be the same as the 26-inch pipe data, which is 400 ksi for $\bar{\epsilon} < 2.5\%$ and 110 ksi for $\bar{\epsilon} > 2.5\%$ where $\bar{\epsilon}$ denotes the equivalent total strain.

Weld crown and drop through or suck up were not modeled in this mesh. These parameters were found by Derbalian et al [8] to have only slight significance in the stress analysis.

Residual axial stresses of the form $\sigma_z = F(z)G(r)$ were included in the pipe as an initial condition. At each cross-section, axial equilibrium is satisfied i.e., $\int_A \sigma_z r dr d\theta = 0$ where A is the cross-sectional area at constant z, r is the radial distance. Circumferential stresses were assumed to be the same as axial stresses i.e. $\sigma_\theta(r,z) = \sigma_z(r,z)$. Shear and radial stresses are an order of magnitude smaller and thus are assumed to be zero. The profile of the residual stresses is shown in Fig. 2 where a cosine through thickness distribution is assumed. The maximum residual stress in the HAZ is 24 ksi.

A uniform tensile stress was applied at the end of the pipe and increased up to 136% of the base metal yield at 550°F, i.e. 31.28 ksi. The quantity 1.36 represents the fully plastic moment of a 4-inch diameter pipe divided by the elastic limit moment. Internal pressure equal to 1100 psi was added similar to the experimental procedure used by General Electric in their pipe test lab.

At 14 ksi applied stress (this load corresponds to an operating condition) some yielding along the ID in the HAZ and weld metal occurs but the plastic strains are very small; maximum values are 0.03%. Stress contours are shown in Fig. 3, maximum axial stress is 35 ksi at the ID in the HAZ. Note that the axial stresses at 1/3 inches away from the weld metal and in the HAZ are completely tensile.

When the load was increased to 1.36 times the base metal yield, the pipe was fully plasticized. The maximum plastic strain equals 1.7% and occurs in the HAZ at the ID. The pipe is completely under tensile axial stresses ranging from 26.3 ksi to 43 ksi. Axial strains are about the same magnitude as the total (equivalent) plastic strain meaning that axial strains are the predominant strain component. Hoop stresses in the HAZ at the ID range from 2 ksi to 9 ksi. Recall that residual hoop stresses were 24 ksi in the weld metal. This indicates that the loading produces compressive hoop stresses. When the load was removed, the residual stresses were significantly reduced (see Fig. 4). Along the ID in the HAZ, maximum axial stresses are 3.8 ksi, and in the weld metal at the ID, were nearly zero.

2.2 26-Inch Diameter Welded Pipes

Unlike the smaller 4-inch diameter pipes, the 26-inch pipe has residual stresses which are somewhat axisymmetric. The throughwall residual axial stress distribution is shown in Fig. 5. This shape was obtained from Shack's measurements [4] and analytical FE results of Rybicki [2]. Residual stresses are tensile at the ID, but they become compressive a short distance away from the ID. Material yield stresses in the HAZ vary linearly (with distance) from 50 ksi to 27 ksi and the yield stresses for the base metal and weld metal are taken to be 23 ksi and 53 ksi, respectively, at 550°F. Work hardening slopes are the same as the 4-inch pipe. Circumferential residual stresses are assumed to be the same as axial stresses. For reasons previously given, radial and shear residual stresses are assumed to be zero.

A tensile stress was applied to the end of the pipe. At 14 ksi applied stress, the pipe is mostly elastic; only a small part of the pipe in the HAZ and near the counterbore yielded. The plastic region and axial stresses are shown in Fig. 6. The maximum plastic

strain was 0.04% and maximum axial stresses along the ID are 33 ksi. At 0.4 inches from the weld centerline, the throughwall axial stresses are plotted in Fig. 7. Stresses at the ID start with tension (33 ksi), at 0.2t from the inner surface of the pipe (t = thickness), axial stresses become compressive. This compressive stress can prevent a crack growth through the wall. It is believed that the crack discovered in the German KRB unit A, 26-inch pipe was retarded because of the compressive stress field. Harris [9] computed the stress intensity for an operating load* and found that the stress intensity at some distance away from the ID becomes compressive, hence inhibiting the crack growth.

The applied stress was increased to 1.3 times the base metal yield at 550°F, i.e., $1.3 \times 23 = 29.9$ ksi. The factor 1.3 represents the fully plastic moment divided by the elastic limit moment for a 26-inch pipe. At this load, the pipe is fully yielded. Maximum plastic strains in the HAZ are of the order of 1%. Maximum axial stresses in the HAZ are 50 ksi. The pipe is fully plastic at this load

3. Induction Heating Stress Improvement

In Section 2 of this paper, welded pipes in their as-welded condition were investigated. These pipes were under tensile residual stresses along the inner surface of the pipe. The combination of such tensile ID residual stresses with dissolved oxygen in the water and material sensitization of the 304 stainless steel have been identified as the cause for intergranular stress corrosion cracking in the BWR welded pipes.

A logical measure against cracking is to adopt countermeasures that will alleviate every single cause of cracking. That is, 1) improve the residual stresses, 2) improve the water chemistry, and 3) use a material which does not sensitize. This is basically the approach that the Electric Power Research Institute is pursuing. This part of the paper describes stress analysis of 4-inch diameter pipes which have had residual stress improvement (RSI). The object is to quantify and assess the improvement that RSI pipes provide over the reference/as-welded pipes.

One of the promising residual stress improvement techniques pioneered by the Japanese nuclear industry is the Induction Heating Stress Improvement (IHSI). This technique is already implemented in Japanese plants. Briefly, the object is to produce compressive residual stresses along the inner surface of the pipe. IHSI is achieved by heating the outer surface of a pipe with an induction coil while cooling water passes through the pipe, as shown in Fig. 8. The high temperature along the OD produces plastic flow on the surface and, upon cooling, the ID will be under compression and the OD will be under tension.

It was illustrated in Section 2.1, that if a large load is applied to the pipe such that the pipe becomes fully plastic, the residual stresses will be significantly reduced. If this is the case with IHSI pipes, the favorable compressive residual stresses produced by IHSI may be effaced if an increased or upset loading condition occurs. One of the aims here is to determine the fraction of remaining residual stresses as a function of the maximum applied load in the pipe.

*The stress intensity computed in Ref. [9] used an arithmetically summed stress due to residual and 14 ksi applied load. This is approximately true for a linear elastic stress load, but the procedure does not take into account the stress redistribution due to primarily geometric effects (counterbore) and, secondly, due to some plasticity. For higher loads, plasticity should be accounted for.

3.1 Analysis of a 4-Inch Diameter IHSI Pipe With Internal Pressure

A 4-inch diameter welded pipe with IHSI (see Fig. 1) was loaded in tension and then unloaded from several load levels to determine the remaining residual stresses. In these runs, an 1100 psi internal pressure* was included. Yield stress values in the pipe used in the analysis are shown in Fig. 1. These values are obtained from GE's experimental results [7]. IHSI residual stresses used in this analysis were obtained from Ishikawa Harima's report [10] and are shown in Figs. 9 and 10. As expected, when the applied stress was below the initial yield point, the residual stresses remained unchanged, but when the tensile load was increased, causing plasticity in the pipe, the residual stresses were redistributed and, upon unloading, they diminished in magnitude along the inner surface of the pipe. Fig. 11 shows the percentage of recoverable residual stresses along the ID in the HAZ as a function of the stress from which unloading† took place. Up to 15 ksi applied tensile stress, the residual stresses remain unaffected. Beyond that load, the remaining residual stresses diminish. Unloading from 35 ksi tension leaves only 15% of the original compressive stresses.

At 14 ksi applied stress, part of the pipe yielded near the OD. Fig. 12 shows the plastic region and axial stresses. Plastic strains are very small (0.017% maximum). Along the ID in the HAZ, axial stresses range from 0.9 to 5.5 ksi compression. This shows that the ID of the pipe (in the HAZ) at operating loads is under compressive stress, which is desirable from a stress corrosion cracking point of view.

At 31.28 ksi stress (1.36 x 23 ksi), the pipe is fully plastic. The HAZ has plastic strains ranging from 0.07% near the weld metal to 0.23% near the base metal. Maximum plastic strain in the base metal is about 0.55%. Axial strains range from 0.18% near the weld metal to 0.4% near the base metal. The entire pipe is under tension. Throughwall axial stresses in the HAZ along the fusion line range from 28 ksi at the ID to 43 ksi at the OD. These stresses compared to the as-welded pipe are lower.

The remaining residual axial stresses after unloading from 31.28 ksi are shown in Fig. 13. In the HAZ along the ID, remaining residual stresses ranged from 10 ksi compression near the weld metal to 6 ksi compression near the base metal.

4. Conclusions

In this paper, 4-inch diameter as-welded and IHSI welded pipes and a 26-inch diameter as-welded pipe were analyzed, using the finite element method. Residual stresses that are generated during the welding process were included in the finite element analysis as an initial state of stress. The pipes were loaded in tension beyond the yield point of the base metal to investigate the redistribution of residual stresses. Cyclic loading (load in tension and then unload) was analyzed for the IHSI 4-inch diameter pipes to determine if the beneficial compressive ID residual stresses were removed during an increased loading.

Measurements of residual stresses in 4-inch diameter as-welded pipes indicate circumferential and radial variation of stress. Instead of analyzing a pipe with this 3 dimensional state of residual stresses, which would require large computational effort, axisymmetric

*Note that an equivalent axial $\frac{Pr}{2t}$ stress was not added. (P=pressure, t = thickness of pipe, r = radius of pipe.)

†Additional load cycles do not change the remaining residual stresses because of shakedown. Kinematic hardening was assumed in the incremental plasticity formulation.

states of residual stresses were analyzed as approximation. 26-inch diameter as-welded pipes and 4-inch diameter IHSI pipes have residual stresses which are nearly axisymmetric. Therefore, the axisymmetric finite element models used here were a good representation for those welded pipes.

4.1 Specific Conclusions

The following conclusions were derived for:

4-Inch Diameter IHSI Pipes

Up to 15 ksi applied stress, the residual stresses are unaffected (i.e., upon unloading, the residual stresses are recovered). This load is above the normal operating stress level. (Plasticity begins at this load level.)

Residual stresses in a welded pipe will be removed (under a cyclic load) if a sufficiently large force is applied to the pipe, such that the pipe is fully plastic.

The residual stresses (along the ID in the HAZ) will be completely removed if a tensile load up to 39 ksi is applied to the pipe and then unloaded.

If the pipe is partially yielded, some of the residual stresses are recovered upon unloading. For example, a 25 ksi tensile cyclic stress load will remove only 30% of the compressive ID stresses in the HAZ.

At operating loads (14 ksi axial tension), the pipe ID is under compressive axial stresses ranging from 7.5 to 2.5 ksi in the HAZ. (An 1100 psi internal pressure is included.

Axial strains along the ID in the HAZ at operating loads (14 ksi stress) are small and fairly uniform ~ 0.05%.

At 31.28 ksi tension load, (i.e., $1.36 \sigma_y$, where $\sigma_y = 23$ ksi is the base metal yield at 550°F) the axial stresses along the ID are tensile, ranging from 27 to 35 ksi in the HAZ. Axial strains range from 0.24% to 0.34% in the HAZ.

4-Inch and 26-Inch As-Welded Pipes

At operating loads (14 ksi tension), the throughwall axial stresses in a 26-inch pipe are tensile at the ID surface in the HAZ, but they become compressive at 0.25 inches from the surface (i.e., at $0.2t$ where $t =$ pipe thickness). These compressive stresses can prevent crack growth.

For the same load (14 ksi tension) the throughwall axial stresses in a 4-inch diameter as-welded pipe with internal pressure are tensile along the ID and remain tensile through most of the thickness. Along the fusion line, tensile axial stresses in a 4-inch pipe extend through 70% of the thickness compared to 20% for a 26-inch pipe.

The peak stress at 14 ksi load along the ID in the HAZ is 38 ksi for the 4-inch pipe and 26 ksi for the 26-inch pipe.

Maximum stresses and strains along the ID are larger for a 4-inch diameter pipe than a 26-inch diameter pipe at the corresponding fully plastic loads.

4.2 General Conclusions and Recommendations

From the finite element analyses, it was concluded that IHSI will provide a definite improvement over as-welded 4-inch pipes. For example, at operating loads, the inner surface of the 4-inch pipe is under compression with IHSI but without IHSI will be in tension with a peak stress of 38 ksi at the ID. The compressive residual stress along the ID in the HAZ will be slightly reduced if an upset loading occurs but, during operating loads (up to 15 ksi tension), residual stresses are unaffected. It would require a very large overload (39 ksi) to almost completely remove the residual compressive stresses.

In addition to having compressive stresses along the ID which prevent stress corrosion crack growth, the IHSI pipe will, in general, have lower stresses than the as-welded pipe, and also a larger load is required to yield the IHSI pipe vs. the as-welded 4-inch pipe.

The 26-inch diameter as-welded pipe has throughwall axial stresses at operating load which become compressive a short distance from the inner surface which is under tension. This compressive stress prevents the growth of cracks. Whereas the 4-inch as-welded pipe will be predominantly under tension for the same load. The important question here is, will the 26-inch pipe benefit from IHSI? It is believed that the crack discovered in the German KRB plant 26-inch as-welded pipe was retarded because of the compressive stress field. It is then recommended that a 26-inch pipe with IHSI be analyzed and compared to the as-welded pipe. It is also worth commenting that the residual stress data for a 4-inch diameter as-welded pipe is not axisymmetric and, therefore, the finite element model which used an axisymmetric formulation (to reduce computational cost) should be regarded as approximations to the actual case. Certainly, a 3 D pipe analysis will be needed to properly model the residual stresses, but the computational effort may be somewhat costly.

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THROUGHMALL STRESSES:

$$\sigma_z = F \cos \left(\frac{\pi}{2} (r-r_1) - \phi \right)$$

$$\phi = 0.0514861 \text{ RADIANS, } F = \text{RESIDUAL STRESS ALONG I.D.}$$

$$\theta = \alpha$$

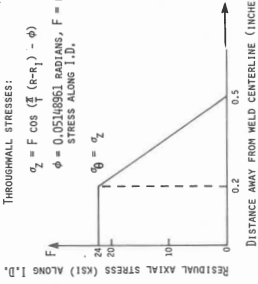


FIGURE 2 - RESIDUAL STRESSES IN 4-INCH DIAMETER WELDED PIPE.

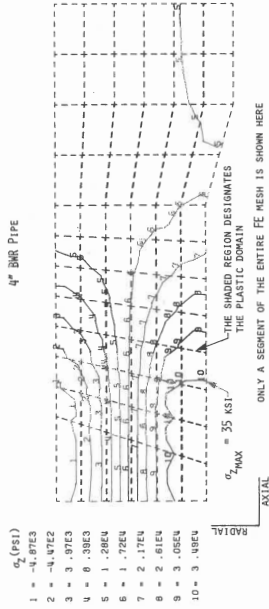


FIGURE 3 - AS WELDED: AXIAL STRESS AT 14.0 KSI (WITH I.D. PRESSURE).

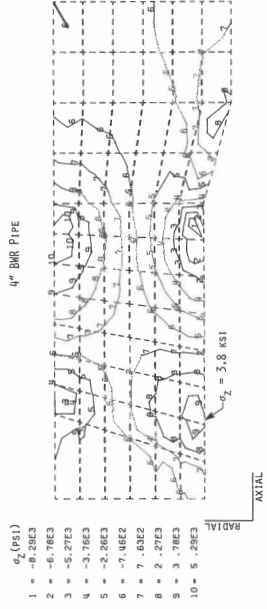


FIGURE 4 - AS WELDED: AXIAL STRESS AFTER UNLOADING.

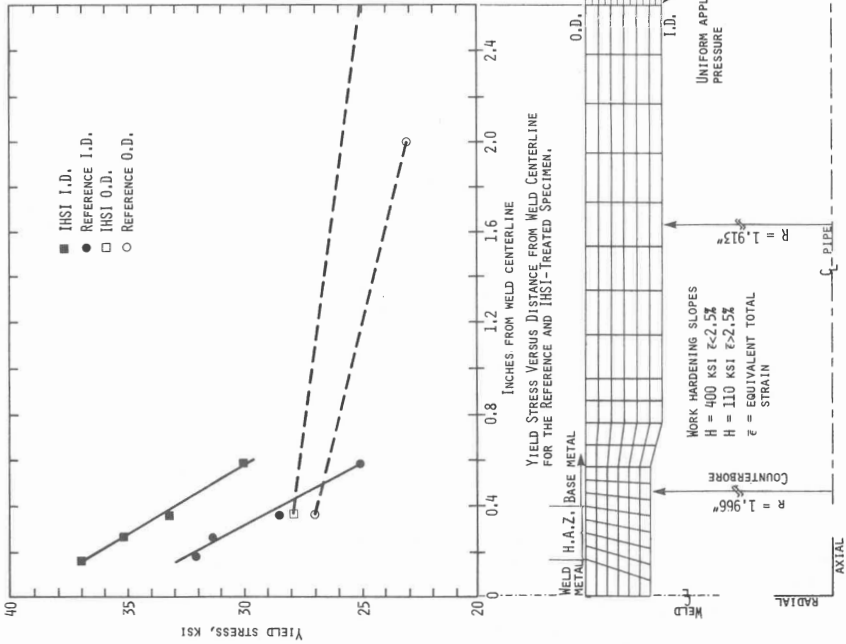


FIGURE 1 - 4-INCH DIAMETER BWR PIPE.

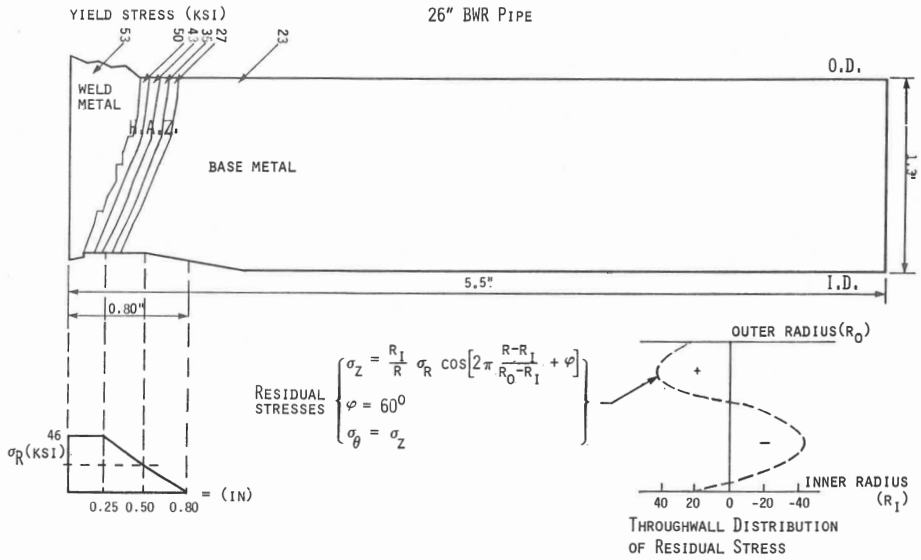
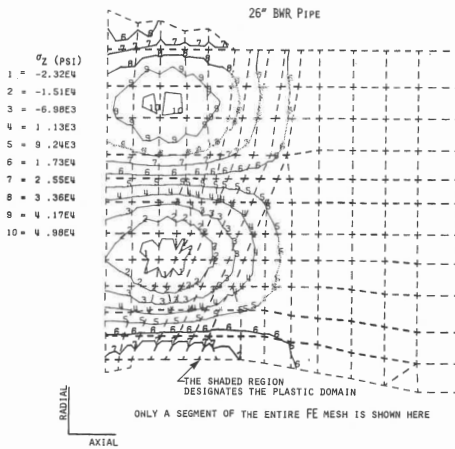


FIGURE 5 - RESIDUAL STRESSES IN 26" BWR PIPE.

FAA-M-81-1-5



FAA-M-81-1-5

FIGURE 6 - AS WELDED: AXIAL STRESS AT 14,0 kSI PULL.

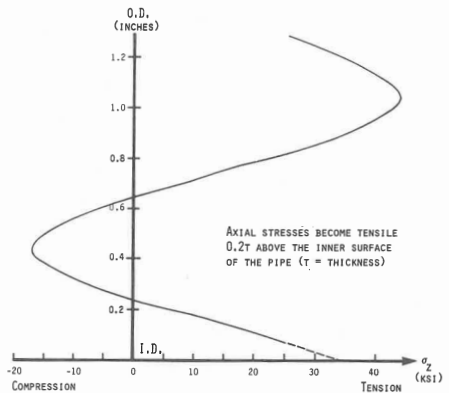


FIGURE 7 - THROUGHWALL AXIAL STRESSES IN A 26-INCH PIPE AT 0.4 INCHES AWAY FROM THE WELD CENTER LINE AT 14 kSI LOAD.

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FM-M-81-1-5

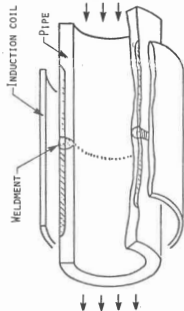


FIGURE 8 - SCHEMATIC OF INDUCTION HEATING STRESS IMPROVEMENT (IHSI) TECHNIQUE.

FM-M-81-1-5

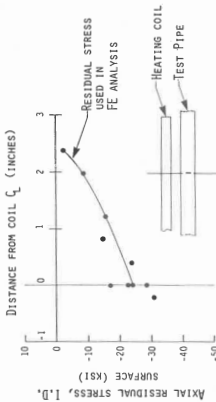


FIGURE 9 - RESIDUAL STRESS DISTRIBUTION IN 4" (IHSI) PIPE.

FM-M-81-1-5

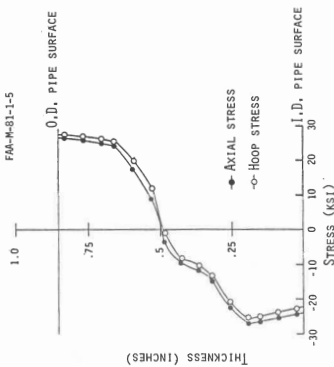


FIGURE 10 - PROFILE OF THE RESIDUAL STRESS DISTRIBUTION ACROSS THE THICKNESS.

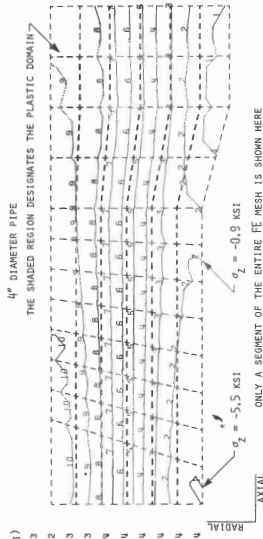


FIGURE 12 - IHSI: AXIAL STRESS AT 14,0 KSI. ONLY A SEGMENT OF THE ENTIRE FE MESH IS SHOWN HERE

FM-M-81-1-5



FIGURE 13 - IHSI: AXIAL STRESS AFTER UNLOADING.

FM-M-81-1-5

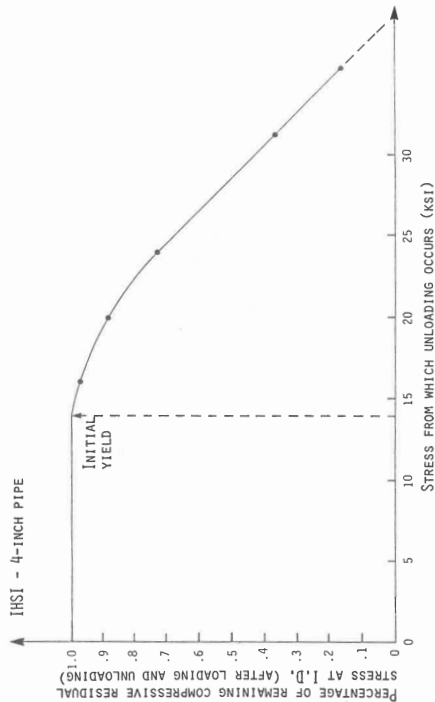


FIGURE 11 - PERCENTAGE OF REMAINING RESIDUAL STRESSES IN HAZ (ALONG I.D.) AFTER A LOADING CYCLE.