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플라스틱 파이프의 잔류응력에 관한 연구 I. 측정방법 및 해석

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Residual Stresses in Plastic Pipes and Fittings I. Methods for Experimental Analysis

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요 약: 폴리에틸렌 파이프와 피팅내에 존재하는 잔류응력의 크기와 분포를 시간의존 특성으로 변화된 세 가지의 측정법을 각각 적용하여 연구하였다. 링 및 축 절단 방법은 간단하지만 이들 구조물내 외면에 존재하는 테와 축 방향의 최고 잔류응력들의 근사치를 구하는데 한정되었고, 터닝과 보링방법은 측정과 그 해석에 있어서 다소 복잡하지만 잔류응력의 크기와 분포를 동시에 정확히 구할 수 있는 장점을 지니고 있었으며, 홀드릴닝 방법에서도 유사한 결과를 얻을 수 있었다. 터닝 과 보링은 테쪽 방향의 잔류응력을 얻는데 국한되며 홀드릴닝은 양방향 동시측정이 가능하지만 잔류응력의 전체 분포를 구하기 위해서는 정확한 예비검정이 요구되므로 표면으로부터 한정된 깊이의 잔류응력을 구하는데 사용되었다. 압출성형된 파이프와 사출성형된 피팅들로 부터 얻어진 결과들을 통해 잔류응력은 이 축 방향 모두에 비슷한 크기로 존재하고 있으며, 파이프의 경우 내면은 인장, 외면에는 압축잔류응력이 걸린 비대칭 포물선 분포를 이루고 있고 피팅은 양쪽면 모두에 압축 그리고, 벽 중앙 부분에는 인장잔류응력이 걸린 대칭 포물선 상태로 분포하고 있음을 알 수 있었다.

ABSTRACT: Three experimental techniques have been applied to determine residual stresses in polyethylene pipes and fittings. The ring and axal slitting methods were the simplest to perform, however the information obtained was limited to approximating the maximum residual stress values at the inner and outer surfaces. The boring and turning methods were more involved both in experiment and analysis, yet the methods had the advantage of providing more accurate residual stress values and their distributions through the wall thickness. It has been found that the best results can be obtained by coupling both boring and turning methods together. Hole-drilling method of analysis was also investigated and the preliminary findings indicate that the results well replicates those obtained with boring and turning methods. This technique also had the capability for simultaneous measurement of stresses in both circumferential and longitudinal directions. From the measurements made thus far indicate that a biaxial tensile residual stress is present on the inner surface of the extruded plastic pipe and a biaxial compressive residual stress exist on the outer surface. The slitting method has under-estimated the compressive stresses at the pipe outer surface and overestimated the tensile stresses at the inner wall. For the injection molded fittings, a parabolic distribution is present, with compressive near both surfaces and tensile at the center region of the wall thickness. The use of slitting method to obtain a first approximation to residual stress recovery upon annealing is also presented.

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Keywords: plastic pipes and fittings, residual stress and distribution, slitting methods, boring and turning methods, hole-drilling method.

INTRODUCTION

Residual stresses in polymeric materials is by now a well-established phenomenon and their effects on deformation and fracture behavior of polymers have been investigated.[1-4] However, such studies on tubular plastic structures such as pipes and fittings are very limited.[5,6] In thermoplastic polymers, residual stresses are often produced as a result of melt processing.[7,8] During such a processing inhomogeneous deformation of the melt by the imposed shear stress that when combined with non-uniform temperature distribution during solidification of the polymer, often leaves the part in a state of residual stress. The melt temperature of the material and the pressure change during solidification can also influence residual stress formation. The plastics pipes are extruded product and the fittings used for joining the pipes are generally injection molded. While the maximum value of residual stress in them is affected by the melt temperature and the cooling rate, the sign of the stresses at outer and inner portions of the wall thickness is governed by the method of cooling. The most common technique for cooling pipe extrudate is by cold water spraying onto outer wall as the pipe passes through a series of spray tanks. The inner wall on the other hand is maintained in contact with ambient air. This operation in combination with low thermal conductivity of polymers inevitably produces through wall thickness temperature gradient. As a result, longitudinal and circumferential residual stresses are expected in the pipes, with signs of stresses being different at the outer and inner surfaces. If in case that the cooling rates on surfaces are maintained approximately equal, as in injection molded fittings, then a symmetric residual stress state would be achieved, compression in both the outer and inner surfaces and tension in the mid wall thickness. The static force equilibrium requires that the signs and the magnitudes of resultant residual forces need to balance, hence through wall thickness stress distributions similar to ones shown in Fig. 1a and 1b are anticipated for the above described cases, respectively. The rate cf cooling and melt temperature during processing may also affect the microstructural morphology of the parts including crystallinity and molecular orientation. Thus, the measured differences in residual stress for a manufacture′s pipe or fitting may signify a difference in processing condition, which can also affect their mechanical behavior such as stress cracking, creep, fatigue life, impact and fracture strengths. Since residual stresses are easier to determine than structure or molecular orientation in plastics parts, they may serve as a more effective and direct indicator of a process deviation. Thus, their determination may be considered a simpler way of checking the consistency of received pipes and fittings. Residual stress measurement in tubular structures has been an area of concern mostly with metallic structures and specific methods have been developed to analyze for residual stresses in thin and thick walled metal pipes.[9-11] Very little effort has taken place with respect to measurement of residual stresses in tubular plastic structures. Only a few studies have been published on the subject.[6,12-16] However, the same methodology developed for determining residual stresses in metal pipes can be employed for plastic pipes and fittings, although it is necessary to account for the fact that plastics are time dependent materials exhibiting creep and stress

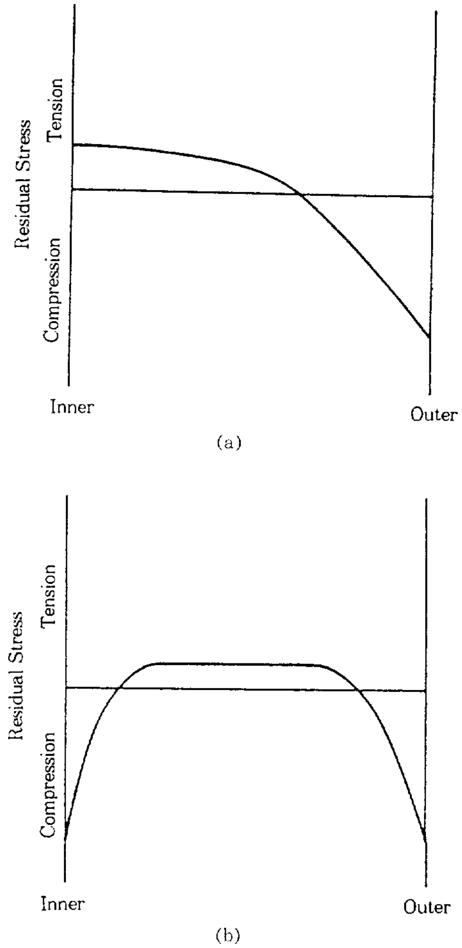

Figure 1. Possible residual stress distributions through wall thickness of pipes and fittings.

relaxation. As a part Ⅰ of this paper series, methods for experimental analysis and results relating to residual stress measurements on plastic pipes and fittings are presented. The effect of pipe assembly process such as the use of fittings and fusion welding on residual stress state is examined in part Ⅱ,[17] and the residual stress effect on stable crack growth behavior in plastic pipes is demonstrated in part Ⅲ.[18] part Ⅳ[19] discusses the annealing effect on deformation and fracture properties of the residually stressed pipe.

EXPERIMENTAL

Materials. Materials utilized for the residual stress measurements were obtained in the form of extruded pipes and injection molded fittings, having several different nominal diameters and Standard Dimensional Ratios (outside diameter to wall thickness ratio). They were the high and medium density polyethylenes, some of which are still being extensively used in natural gas pipeline applications. Four different polyethylene pipe materials investigated were designated as PE2306IA, PE2306IIE, PE3406IIE, and PE3408IIE, referring to differences in density, melt index, pressure rating, material composition, and manufacture, as described in detail elsewhere.[20] The dimensions of the pipes and fittings used in this study are shown in Table 1 in terms of the Standard Dimensional Ratio (SDR).

Slitting Methods. Residual stresses in both longitudinal (or axial) and circumferential (or hoop) directions (Fig. 2) were determined for three different pipe materials, PE2306IA, PE2306IIE, and PE3408IIE, and for various pipe sizes ranging from 2SDR11 to 8SDR21, using slitting techniques.[12] Two separate variations of the slitting method were employed. For the circumferential stress measurements, ring specimens sectioned from pipes having predetermined arc length removed by axial slitting were used (Fig. 3). If the pipe has residual tensile stress on the inside wall the ring will close, thus reducing its diameter. Stated equivalently, ring diameter increases upon slitting would indicate the presence of compressive residual stress on the inside wall. Hence, by measuring the ring diameter at a specific time, the maximum hoop residual stresses can be calculated by using Equation 1. The longitudinal stresses on the other hand were determined by cutting a tongue of a predetermined length along the longitudinal direction in the pipe length, as shown in Fig. 4. The deflection at the

Table 1. Pipe and Fitting Materials and Dimensions

material	pipe size	fitting size
PE2306 Ⅰ A	1SDR11, 2SDR11, 4SDR11.5, 6SDR11.5, 8SDR11, 8SDR21	2 & 4SDR11
PE2306 Ⅱ E	2SDR11, 3SDR11.5, 4SDR11.5, 6SDR11.5, 6SDR13.5, 8SDR11	
PE3406 Ⅲ E	4SDR11, 6SDR11, 6SDR17	
PE3408 Ⅲ E	2SDR11, 4SDR11.5, 6SDR11.5, 8SDR11	2, 4 & 6SDR9.33

* 2SDR11 refers to a pipe or fitting with 50 mm (2″) nominal diameter and SDR of 11. All fittings were injection molded equal tees.

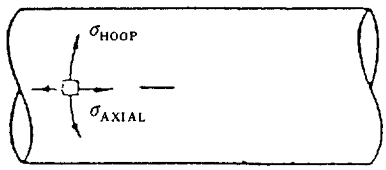

Figure 2. Circumferential (hoop) and longitudinal (axial) directions.

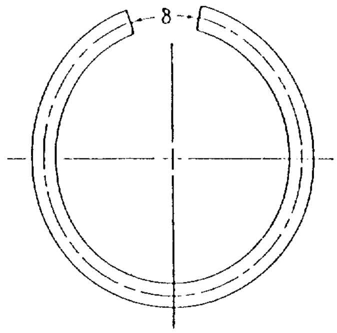

Figure 3. Ring sample geometry for circumferential residual stress measurement.

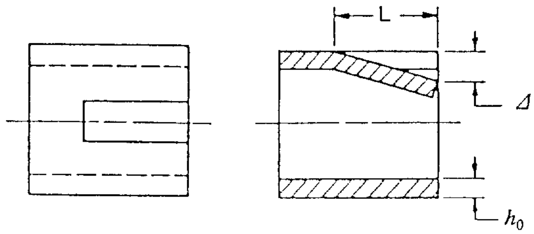

Figure 4. Sample geometry for longitudinal residual stress measurement.

end of the tongue was measured at a specific time, and the maximum longitudinal residual stresses that act on the outer and inner most surfaces were determined through Equation 2.

$$\sigma_{H(max)} = \pm \frac{E(t) \times h_0}{1-\nu} \frac{D_2(t) - D_1}{D_2(t) D_1} \quad (1)$$

$$\sigma_{L(max)} = \pm \frac{E(t)\, h_0\, \Delta(t)}{L^2} \quad (2)$$

Here, $E(t)$ = creep modulus at time t
h_0 = wall thickness
D_1 = mean diameter before slitting
$D_2(t)$ = mean diameter after slitting at time t
ν = Poisson's ratio
$\Delta(t)$ = end deflection of the tongue after time t
L = tongue length

In both cases, to calculate residual stresses, require knowing the value of the time dependent creep modulus of the material, $E(t)$, and the dimensional change that corresponds to the same time interval. To determine $E(t)$, pipe sections were remolded into flat plates and subsequently machined to produce rectangular bar specimens. The $E(t)$ was measured up to 6 days, at room temperature, using a three point bend flexure test method. The change in creep modulus with time is given in Fig. 5.

Following procedures were used for the sample preparation and measurements. Rings were first sectioned from pipes using a band saw and they were then machined into a uniform height (approximately 25 mm) and slit on a milling machine to produce a gap (δ). Slit tongues in samples for longitudinal residual stress measurements were produced by cutting along the predrawn parallel lines in the pipe length. It has been shown that the

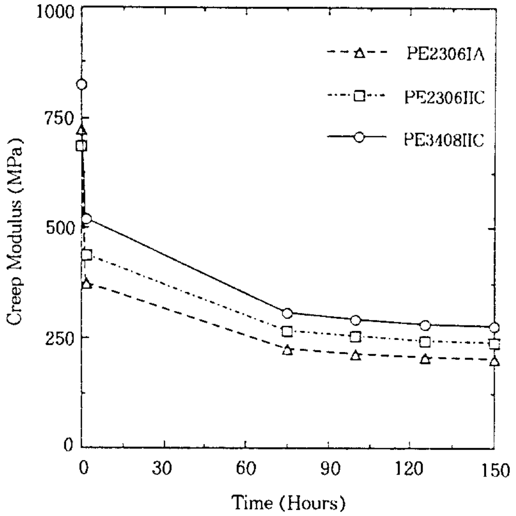

Figure 5. Variation of creep modulus with time.

cutting action itself bring about a minor change in the residual stress state, however limited to local regions in close proximity to the cut surfaces,[18] hence plays an insignificant role in affecting the overall original residual stress state. Optimal slit gap size in the ring samples, and slit tongue ane tongue are lengths in the pipe samples were predetermine for different pipe materials and pipe sizes to ensure the proper release of the bending moment without any self restraint. The change of slit ring diameter and slit tongue end deflection was measured at a specific time, to a nearest 0.025 mm. For most cases the dimensional changes used for the residual stress calculations were obtained 3 to 5 days after slitting.

Turning and Boring Methods. To determine the residual stress distribution in the circumferential direction both turning and boring methods were utilized.[6,13] In the turning method, rings sectioned from pipes and fittings were subsequently turned down from the outside surface inward to various ring thicknesses. A predetermined arc of the ring was then axially slit to produce a gap (δ), as shown in Fig. 6. The gap displacement as a function of the wall thickness was measured

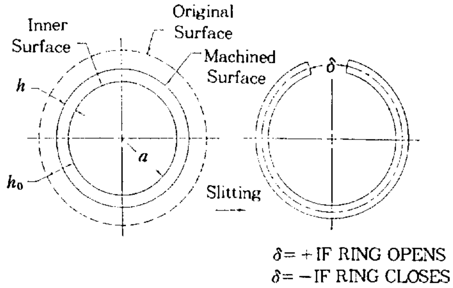

Figure 6. Ring specimen for turning and subsequent ring deflection measurment.

and the residual stress at any given wall thickness was calculated using Equation 3 given below. Similarly, in the boring method where rings of various wall thicknesses were prepared by boring the ring from inner surface to outward, Equation 4 was used to calculate the hoop residual stress for any given wall thickness.

$$\sigma_\theta(h) = \frac{E(t)}{12\pi a^2}\left[4h\delta(h) + h^2\delta'(h) + 2\int_0^h \delta(h)dh\right] + \sigma(o) \quad (3)$$

$$\sigma_\theta(h) = -\frac{E(t)}{12\pi b^2}\left[4h\delta(h) + h^2\delta'(h) + 2\int_0^h \delta(h)dh\right] + \sigma(o) \quad (4)$$

where $\sigma(o)$ is determined from the zero hoop load condition as

$$\int_0^{h_0} \sigma_\theta(h)dh = 0 \quad (5)$$

and σ_θ = circumferential residual stress

δ = gap displacement at time t

$E(t)$ = creep modulus at time t

h = current wall thickness

h_0 = original wall thickness

a = original inside radius

b = orignal outside diameter

$$\delta'(h) = \frac{d\delta(h)}{dh}$$

For Equations 3 and 4, h is measured from the inner surface and outer surface, respectively.

The ring test samples were taken from pipes and fittings and machined to either 12.5 mm or 25 mm heights, depending on the ring diameter. Special sample holding fixtures were designed to closely control the uniformity of the successive turning and boring operations. For smaller diameter rings (50 mm and 100 mm) turning or boring operations to achieve various wall thicknesses were performed in the lathe with the sample being held in round aluminum mandrel mounted to its chuck. The larger diameter rings (150 mm and 200 mm) generally had larger thickness variations. Thus, to assure the uniform layer removal during turning or boring, a sample holding fixture having system of fixed bearings, spring load floating bearings and rollers was designed and used.[6] To minimize the possible heat build up during turning and boring, no more than 0.25 mm depth was removed at any given step. In addition, compressed air was directed at the contact point of the tool insert and the sample surface during material removal. Turned or bored samples were then slit to produce a gap, sized between 16 mm to 32 mm, depending on the ring diameter.

The presence of residual stresses was to change δ with time and δ was measured indirectly by the outside diameter change. To overcome the problem of low stiffness of the rings, especially for those machined to a thin wall thicknesses, a fixture shown in Fig. 7 was designed and used for the accurate measurement. It employed a milling table, on which a ring is held against the parallel plate with an aid of a magnet, and a limit switch which needed very little force (0.2 gm) and displacement (0.008 mm) to activate. The outside diameter was measured at four different locations to a nearest 0.025 mm.

Hole-Drilling Method. In the hole-drilling method,[11] the residual stresses are determined by

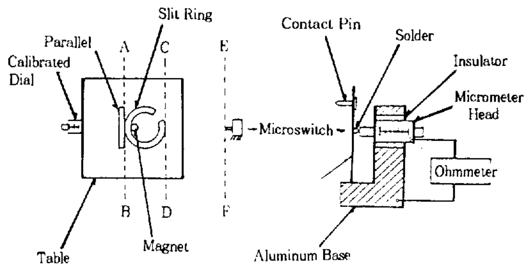

Figure 7. Diagram of outside diameter measurement device.

drilling a small hole in the pipe or fitting walls containing residual stresses to a small depth (δh) and measuring the surface strain changes produced. Therefore, assuming a biaxial stress state exists at depth δh from the outer pipe surface, the surface strain changes in axial ($\delta \varepsilon_L$) and hoop ($\delta \varepsilon_\theta$) directions due to an incremental increase in hole depth are shown in Equations 6 and 7, respectively.

$$\delta\varepsilon_\theta(h) = A_1\frac{\sigma_\theta(h)}{E(t)} + \nu A_2\frac{\sigma_L(h)}{E(t)} \quad (6)$$

$$\delta\varepsilon_L(h) = A_1\frac{\sigma_L(h)}{E(t)} + \nu A_2\frac{\sigma_\theta(h)}{E(t)} \quad (7)$$

Where, A_1 and A_2 = constants for a specific δh
$E(t)$ = creep modulus at time t
ν = Poisson's ratio

Equations 6 and 7 can be rewritten to solve for stresses, σ_θ and σ_L, as shown in Equations 8 and 9, respectively.

$$\sigma_\theta(h) = \frac{E(t)}{A_1^2 - A_2^2\nu^2}\left[A_1\,\delta\varepsilon_\theta(h) + A_2\nu\,\delta\varepsilon_L(h)\right] \quad (8)$$

$$\sigma_L(h) = \frac{E(t)}{A_1^2 - A_2^2\nu^2}\left[A_1\,\delta\varepsilon_L(h) + A_2\nu\,\delta\varepsilon_\theta(h)\right] \quad (9)$$

Constants A_1 and A_2 are pre-determined by calibration to a known stresses-distribution. Thus, with known values of E, ν and the calibration stress σ_x, the constants A_1 and A_2 for any corresponding depths δh can be evaluated by using relations given in Equations 10 and 11, respectively.

$$A_1 = \frac{E\delta\varepsilon_x}{\sigma_x} \quad (10)$$

$$A_2 = -\frac{E\delta\varepsilon_y}{\nu\sigma_x} \quad (11)$$

The hole-drilling method was applied directly on pipes and fittings by using Micro-Measurement 125RE pattern strain gage rosette, whose design incorporated a centering mark for aligning a drilling tool precisely at the center of the gage circle. Rosettes were bonded to the pipe and fitting surfaces by following the procedure given by the Micro-Measurement Inc. Hole-drilling was performed by using RS-200 milling kit which produced consistently straight, true and clean holes. The surface strain data acquisition was achieved by the Micro-Measurement System 4000. The data acquisition began immediately after the hole was drilled and the strain data was collected at every 30 minutes interval up to 50 hours, at which time the strain change has leveled off. The residual stresses were calculated using the strains at 50 hours from Equations 8 and 9.

RESULTS AND DISCUSSION

Slitting Methods. The results obtained from the slitting methods are summarized in Table 2. It is interesting to note that the inside surface of the pipe is in a state of maximum biaxial residual tension while the outside surface is in maximum compression. Further, not only the residual stresses can vary within one size, but also differences in size and the extruder can affect their magnitude.

Table 2. Residual Stresses in Polyethylene Pipes as Determined by the Slitting Methods

pipe resin	pipe size	maximum residual stress (MPa)	
		circumferential*	longitudinal*
PE2306 IA	2SDR11	2.82	2.73
	4SDR11.5	2.61	2.51
	6SDR11.5	0.71	0
	8SDR11	1.01	1.08
	8SDR21	2.02	2.35
PE2306 IIE	3SDR11.5	2.85	2.66
	4SDR11.5	2.99	3.08
	6SDR11.5	2.90	3.72
	6SDR13.5	2.73	3.19
PE3408 IIE	4SDR11	2.66	2.59
	6SDR11	2.81	3.30
	6SDR17	2.56	3.71

* Maximum value of residual tension at inside surface (at the outside surface same magnitude compression exist: see Equations 1 and 2).

It should be also mentioned that if one desires, it should be possible to produce pipes with low values of residual stress like the ones shown by the PE2306IA 6 & 8SDR11 pipes. The maximum values of residual stress found for most cases were significant percent of the yield stress and does influence some of the mechanical properties of the pipes, as presented in Part Ⅳ.[19] If it is assumed that the residual stresses resulted from rapid cooling, then the longitudinal and circumferential values of residual stress should be similar unless the properties of the pipe were anisotropic with respect to these directions. Table 2 shows good agreements between longitudinal and circumferential stresses in many of the pipes tested, thus, indicating a reasonable isotropy on these pipes existed. It is important to note here that the ring slitting methods are only valid when the residual stress distribution is non-symmetric, as shown in Fig. 1a. The stress state shown will cause a bending moment to occur when a ring is slit or a longitudinal tongue is created. However, if a symmetric residual stress distribution exist (Fig. 1b), as in the case of injection molded fittings described

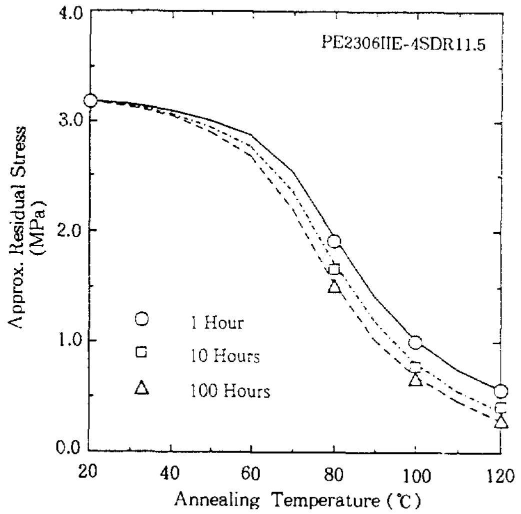

Figure 8. Change of residual stress during thermal annealing.

later, it does not produce bending moment necessary for the slit ring or tongue to open or close. Thus, for latter case the turning, boring or hole drilling methods must be applied to determine the residual stress state, since it can not be assumed that there are no residual stresses if a slit ring does not open or close on itself.

As a final note, the results of the ring slitting method applied to annealed pipes are shown in Fig. 8. One ways to reduce or to eliminate the residual stresses in plastic pipes are through elevated temperature annealing. For the results shown for PE2306IIE-4SDR11.5 pipes, rings sectioned from pipes were first annealed at temperatures for a predetermined times then cooled in ambient air. After cooling the rings were slit and measurements were made at a fixed time for the residual stress calculations. It can be seen that a substantial decrease in residual stress can occur as a result of annealing. In the general case of extruded tubular structures, like pipes, slitting method is a valid way of readily checking the consistency of the pipe quality to a first approximation.

Turning and Boring Methods. When the inner or outer surface layer is removed, radial stresses becomes zero at the new surface created by elastic unloading giving a consequent ring distortion. When the ring is then slit, the pure bending moment on the ring is released to zero and brings about the changes in the gap displacement δ, which becomes greatly enhanced by the subsequent ring distortion. Since δ is only affected by the circumferential residual stress it is used for determining the circumferential residual stresses in the pipe. Given in Equation 12 is the expansion of Equations 3 and 4, written in term of δ and δ'. The plus and minus signs preceeding the right hand side represent turning and boring methods, respectively. Also, for turning and boring, ϕ represents the inside and outside ring diameters, a and b, respectively.

$$\sigma_\theta(h) = \pm \frac{E(t)}{12\pi\phi^2}\Big\{4h\delta(h) + h^2\delta'(h) + 2\int_0^h \delta(h)\,dh - \frac{1}{h_0}\Big(4\int_0^{h_0} h\delta(h)\,dh + \int_0^{h_0} h^2\delta'(h)\,dh + 2\int_0^{h_0}\int_0^h \delta(h)\,dh\,dh\Big)\Big\} \quad (12)$$

Hence, the evaluation of Equation 12 requires knowing $\delta(h)$ and $\delta'(h)$ which are experimentally determined. δ vs. h/h_0 curves for two pipe sizes, PE2306IA 4SDR11.5 and 2SDR11 pipes, obtained from the turning method are given in Fig. 9. From these graphs, $\delta(h)$ was numerically obtained by curve fitting Fig. 9 with a second order polynomial and $\delta'(h)$ was then deduce by differentiating the fitted curve. Since δ vs. h/h_0 for the above mentioned pipes were taken at 96 hours after slitting, the creep modulus at 96 hours was also used for calculating σ_θ, from Equation 12. The results of circumferential residual stress distribution through wall thickness for PE2306IA 4SDR11.5 and 8SDR 11 pipes are shown in Fig.

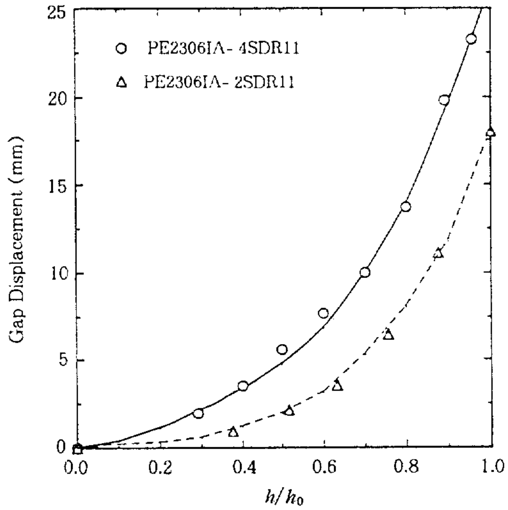

Figure 9. δ vs. h/h_0 at 96 hours for PE2306IA 4SDR11.5 and 2SDR11 pipes.

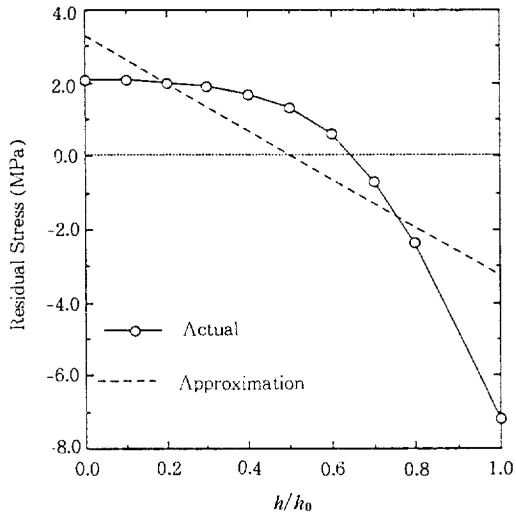

Figure 11. Wall thickness distribution of σ_θ in 8SDR11 pipe.

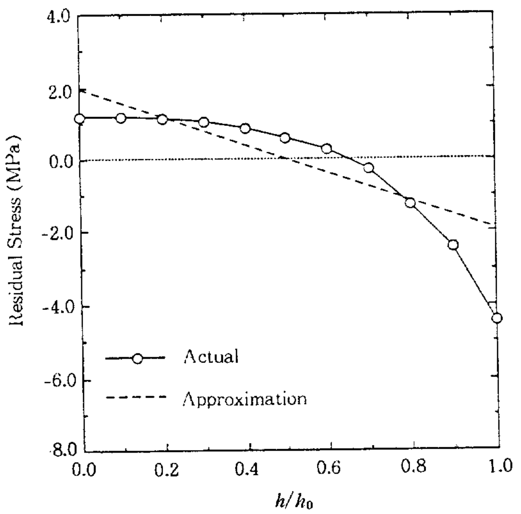

Figure 10. Wall thickness distribution of σ_θ in 4SDR 11.5 pipe.

10 and 11, respectively. It can be observed that the stress profiles obtained by the turning method are parabolic and that about equal areas exist for tensile and compressive stress regions, hence showing the existence of force equilibrium, as was predicted by Equation 5. Superimposed dashed lines in Fig. 10 and 11 are the results from the ring slitting method (Equation 1), extrapolated through the wall thickness using the force equi-librium principle. The slitting method shown represent only an approximation to the actual wall thickness hoop stress distribution. It tends to underestimate the compressive stress on the outer surface but overestimates the tensile stress on the inner surface. However, it still provide a convenient means for a conservative estimation of thresidual tensile stress on the inner surface.

Fig. 12 shows the results of stress distribution in a pipe with data points shown for both boring and turning methods performed separately. In each case the rings were machined completely through their thickness. Both methods are in close agreement, and thus indicates the equivalence of the two methods. It should be noted that δ vs. h/h_0 data becomes difficult to obtain for turned or bored rings when the remaining the wall thickness is less than 30% of its original value. Thus, the determination of the entire stress distribution through the wall thickness by either the turning method or boring method alone has to rely on extrapolation of the data, which can cause some

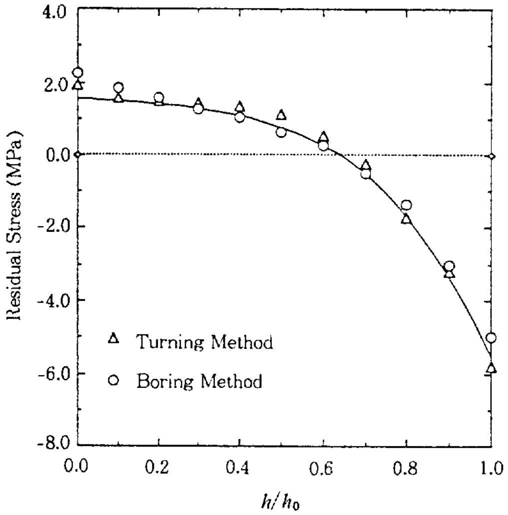

Figure 12. σ_θ distributions obtained from turning and boring methods (PE2306-2SDR11).

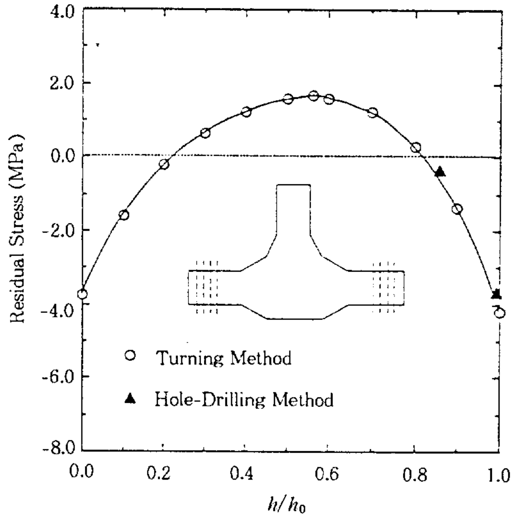

Figure 13. Residual stress distribution in PE3408IIE 6SDR9.33 equal tee fitting by turning and hole drilling methods.

error. These difficulties may be over come by a combination of the two methods in which the stresses in the outer and inner portions are determined separately by the turning and boring methods, respectively. It has been found that the best results were obtained by using the turning data to construct the line for the outer portion of the wall and the boring data for the inner portion. Hence, it is recommended to use a combination of boring and turning to determine the residual stress distributions.

The residual stress distribution obtained for the PE3408IIE 6SDR9.33 injection molded tee fitting is illustrated in Fig. 13. The distribution is parabolic and nearly symmetric and that the residual stresses are compressive near the inner and outer surfaces and tensile in the mid portions of the wall thickness. The difference in the residual stress distributions between the pipes and fittings clearly indicates the value of the residual stress measurements with regard to checking the parts consistency and differentiating the process deviations.

In further developing the turning or boring methods, the following equations are equivalent to Equations 3 and 4 but may be more convenient to use.

$$\sigma_\theta(h_0) = \pm \frac{E(t)}{12\pi\phi^2}\left[h_0^2\delta'(h_0) + 3h_0\delta(h_0)\right] \quad (13)$$

where $\sigma_\theta(h_0)$ is the surface residual stress and

$$\sigma_\theta(h) = \sigma_\theta(h_0) \pm \frac{E(t)}{12\pi\phi^2}\left\{4[h_0\delta(h_0) - h\delta(h)] + [h_0^2\delta'(h_0) - h^2\delta'(h)] + 2\int_h^{h_0}\delta(h)\,dh\right\} \quad (14)$$

Here, the plus and minus signs in each equation apply to turning and boring methods, respectively. For example, the determination of $\sigma_\theta(h_0)$ using Equation 13 requires removal of only a small layer at the inner and outer surfaces. Thus, by coupling the turning and boring method, $\sigma_\theta(h_0)$ can be determined in a simple and accurate manner.

Hole-Drilling Method. An introduction of a hole into a residually stressed parts relaxes the

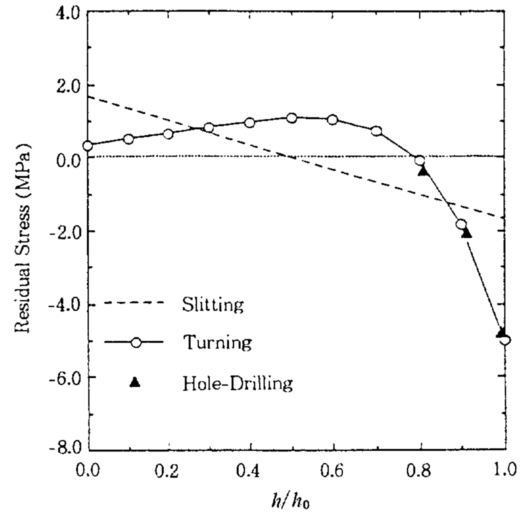

Figure 14. Comparison of turning and hole-drilling methods for distribution.

stresses at that location since the stress normal to newly formed hole surfaces must relax to zero. The elimination of normal stress at the hole boundary reduces the stress in the immediate surrounding region, causing the local surface strains to change correspondingly. As a consequence, the hole drilling method measures the strains produced as a result of the residual stress relaxation with hole depth, which is the necessary data for determining the through wall thickness stress distribution. Also, by using proper strain gage rosettes, biaxial stresses in the pipe wall can be simultaneously determined in a test, as well as the directions of the principle stress components. The results from the hole drilling method and turing method are compared in Fig. 13 and 14 for PE3408IIE 6SDR9.33 fitting and PE3408IIE 8SDR11 pipe, respectively. σ_θ from the hole-drilling method agrees very well with the results from the turning method. These results confirm the validity of both Turning and hole-drilling methods as an accurate means of measuring the residual stresses in plastic pipes and fittings. The constants A_1 and A_2 in Equation 8 was taken as 1. This is valid up to a hole depth twice the diameter of the drill used, hence the outer 20% of the total wall thickness. For deeper depths, the constants must be determined by Equation 10 and 11 using calibration, which at this time is not available. It is interesting to note that PE3408IIE pipes all had stress distribution similar to one shown in Fig. 14. That is, unlike other pipe types, the maximum residual tension is located near the center portion of the pipe wall. Such difference may again be used as an indicator for the process deviation.

CONCLUSIONS

It has been shown that slitting methods, turning and boring methods, and hole-drilling method can be used for measuring residual stresses in plastic pipes and fittings. All of the methods measured stress recovery on deflection or distortion to achieve new stress equilibrium and that plastics are time dependent materials. Hence, it was important to consider the creep modulus for establishing residual stress levels in pipes and fittings. The measurements revealed that a biaxial tensile residual stress state exist in the inner wall portion of the plastic pipe and a biaxial compressive residual stresses were present in the outer portion. For fittings, nearly a symmetric parabolic residual stress distribution was found and that the outer and inner surface regions were under compression while tensile in the mid-portion of the wall thickness. The slitting methods provided a first approximation to the actual stresses at the inner and outer pipe surfaces. It underestimated the maximum residual stress value at the outer surface while overestimating it at the inner surface. However, since the methods are simple to perform, it can be utilized for a quick check of the pipe consistency or characteristics, including the effect of annealing. The slitting methods are not applicable when residual stress distribution is symmetric.

The turning and boring methods can provide accurate information on residual stress distributions through the pipe and fitting wall thicknesses. It was found that the best results were obtained by coupling the turning and boring methods together. The limitation of this method is that only the circumferential residual stress can be determined. The hole-drilling method is also a valid technique for the residual stress measurement and if properly applied, the method can simultaneously measure the hoop and axial residual stresses. However, since the method required the calibration constants to be predetermined for each hole depth of interest it was only applied to regions near the outer surface.

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