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ON THE INFLUENCE OF THE UOE FORMING PROCESS ON MATERIAL PROPERTIES AND COLLAPSE PRESSURE OF DEEPWATER PIPELINES. EXPERIMENTAL WORK.

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Abstract

Large diameter pipes for onshore and offshore applications are manufactured using the UOE process. The manufacturing process consists in the cold forming of heavy plates followed by welding and then by an expansion. It has been demonstrated in previous work that, for deepwater applications, the cold forming process involved in UOE pipe manufacturing significantly reduces pipe collapse strength. To improve the understanding of these effects, Tenaris has embarked on a program to model the phases of the UOE manufacturing process using finite element methods.

Previous phases of this work formulated the basis for the model development and described the 2D approach taken to model the various steps of manufacture. More recent developments included modeling enhancements, some sensitivity analyses, and comparison of predictions to the results of full-scale collapse testing performed at C FER. This work has shown correlations between manufacturing parameters and collapse pressure predictions.

The results of the latest phase of the research program are presented in this paper. This work consists of full-scale collapse testing and extensive coupon testing on samples collected from various stages of the UOE pipe manufacturing process including plate, UO, UOE, and thermally aged UOE. Four UOE pipe samples manufactured with varying forming parameters were provided by Tenaris for this test program along with associated plate and UO samples. Full-scale collapse and buckle propagation tests were conducted on a sample from each of the four UOE pipes including one that was thermally aged. Additional coupon-scale work included measurement of the through thickness variation of material properties and a thermal ageing study aimed at better understanding UOE pipe strength recovery.

The results of these tests will provide the basis for further refinement of the finite element model as the program proceeds into the next phase.

1. Introduction

The Tenaris Group is performing work aimed at understanding the mechanical and material behaviour of offshore linepipe when subject to external pressure [1-4]. This work involves developing advanced finite element analysis models to predict pipe behavior during the manufacturing process and under external pressure, as well as performing detailed geometric measurements, material coupon tests, coupon scale thermal treatment, and full scale collapse tests.

Four samples of 20 inch diameter, 1 inch wall thickness, grade X70 UOE pipe were supplied by the Confab Industrial S.A. plant in Brazil for testing. Each pipe sample was accompanied by a pair of associated plates and UO pipes as indicated in Figure 1.

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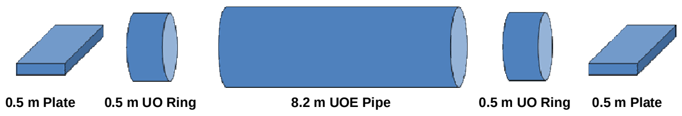

Figure 1. Specimen schematic

This paper presents the results of coupon testing on material at various stages of the UOE pipe forming process, including the as-produced plate, the un-expanded tube, the final UOE form, and the final UOE form after thermal treatment, along with full-scale collapse and buckle propagation results. Table 1 summarizes the testing performed on the supplied samples at C-FER's facility in Edmonton, Canada. The forming parameters of the four pipe samples provided are also provided in Table 1.

Table 1. Testing Summary with Forming Parameters

Pipe	UOE	UO	Plate	L0 (mm)	PBE (mm)	CR (%)	PAE (mm)	ER (%)
1	Collapse and Coupon Tests	Unused	Coupon Tests	1,510.5	1,587.1	0.20	1,595.8	0.55
2	Collapse and Coupon Tests	Unused	Unused	1,511.5	1,583.9	0.47	1,597.6	0.86
3	Collapse and Coupon Tests Through-thickness Coupon Tests	Coupon Tests	Coupon Tests	1,513.5	1,583.7	0.61	1,597.2	0.85
4	Full-scale Thermal Treatment Collapse and Coupon Tests Thermal Coupon Tests	Unused	Coupon Tests	1,505.5	1,582.7	0.16	1,594.9	0.77

Where:
L0: Initial plate width
PBE: Perimeter before expansion
CR: Compression Ratio = {[(L0 + π × thickness) / PBE] – 1} × 100 (%)
PAE: Perimeter after expansion
ER: Expansion Ratio = {[(PAE / PBE) – 1] × 100 (%)

2. Experimental Facilities

The facilities used for the experimental work included C-FER's Deepwater Experimental Chamber (DEC), a Materials Testing System (MTS), a coupon-scale thermal treatment system, and a full-scale thermal treatment system. C-FER's DEC was used for all the full scale collapse tests. The chamber has a tested pressure capacity of 62 MPa, with an inside diameter of 1.22 m and an overall inside length of 10.3 m. All tension and compression coupon tests were conducted using C-FER's MTS 1000 servo hydraulic testing machine. The MTS has a rated capacity of 1,000 kN in tension or compression, which is well in excess of the capacity required for this project. Figure 2 shows both facilities.

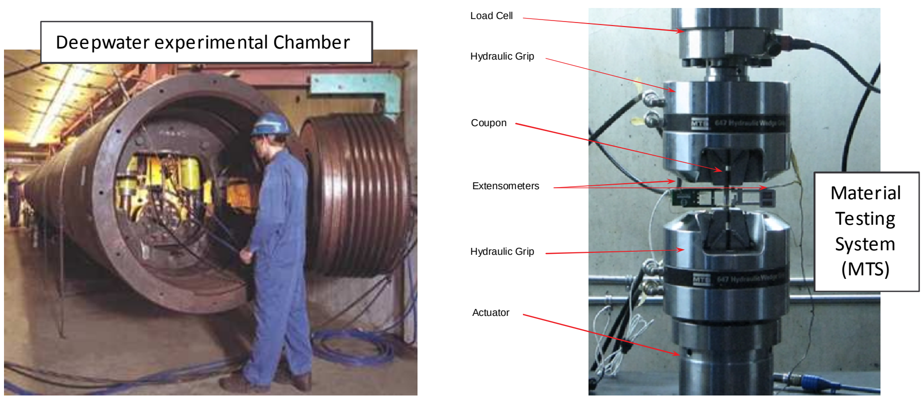

Figure 2. C-FER Deepwater Experimental Chamber and Material Testing System

The full scale thermal coating simulation on Pipe 4 used two 50 m long liquid cooled induction coils, each powered by a Miller ProHeat 35 kW Induction Power Source. For the coupon scale thermal treatment a 2 kW variable frequency computer controlled induction heater was used. The system consists of a power supply, a copper tubing coil that encompasses the coupon and a cooling system that circulates water through the copper coil and the power supply to prevent system overheating. Figure 3 shows a photograph of the two blue induction coils during the actual thermal treatment (left) and the system to perform the coupon's thermal treatment (right).

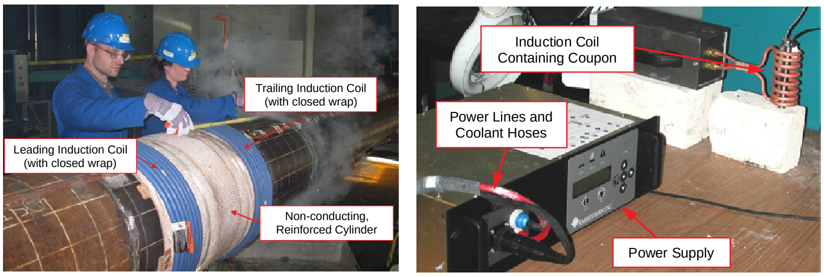

Figure 3. Full scale Thermal Treatment Induction Coil Assemby and Cuopon scale Thermal Treatment Equipment

The induction coil assembly consisted of the following: two liquid cooled induction coils; a reinforced, non conducting cylinder; and two infrared thermocouples. Each flexible induction coil consisted of seven complete closed wraps around the cylinder, which was lined with Teflon® to minimize drag on the outer pipe surface. The coils were spaced 448 mm apart on the cylinder, with the forward coil acting as a "preheat" to bring the pipe temperature to approximately 135°C and the rear coil heating the pipe to approximately 235°C. The infrared thermocouples were used as temperature feedback to control the power output of the ProHeat 35. One infrared thermocouple was placed near the top of the pipe and the other near the bottom. The temperature profile of the pipe was continuously monitored during the thermal treatment process using weld on Type K thermocouples.

3. Specimen preparations

3.1. Full scale Thermal Treatment

Prior to collapse testing, Pipe 4 was subjected to a full-scale thermal cycle simulating a typical fusion-bond epoxy coating process. Before thermal treatment, some material was removed to allow characterization of the "non-thermally-treated" material properties. After thermal treatment, further material samples were removed to allow characterization of the material properties of the thermally-treated pipe.

Thermal treatment of Pipe 4 involved moving the induction coil assembly at a controlled rate with a winch assembly. Thirty two thermocouples were placed at regular intervals along the outer surface of the sample pipe. Sixteen thermocouples were located near the top of the pipe and the other sixteen near the bottom. This allowed for continuous monitoring of the pipe temperature as thermal treatment progressed. The rate of induction coil progression was initially determined from trial runs on sacrificial pipe samples. However, the rate was slightly increased or decreased during the heat treatment depending on the readings from the thermocouples. After approximately 5 minutes at temperature, the specimen was cooled by water quenching. Figure 4 shows a typical temperature profile for the full-scale thermal treatment process.

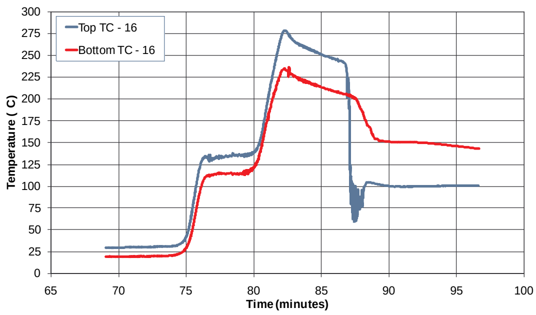

Figure 4. Full Scale Thermal Treatment Results

3.2. End Cap Welding

End plates were welded onto all four pipe samples to facilitate collapse and buckle propagation testing. The end caps were 20 inches in diameter, 4 inches thick, and made of 44W structural plate. A GMAW welding process with an ER70S 2 consumable was used.

3.3. Pipe Measurements

Each of the supplied pipes was measured by Tenaris prior to delivery to C-FER. The outer surface was mapped using the shapemeter [3] and the thickness was also mapped using a standard ultrasonic gauge over a grid made of 16 generatrixes and 75 sections of the pipe. In figure 5, the surface map and Fourier decomposition of the external surface considering the first 12 modes along the pipe length for pipe 1 are shown. It can be clearly seen the seam of the pipe as lighter (higher) line all along the pipe length. The thickness map for pipe 1 is shown in figure 6. For a better visualization, the thickness map does not take into account the weld thickness which has an average value of 26.6 mm.

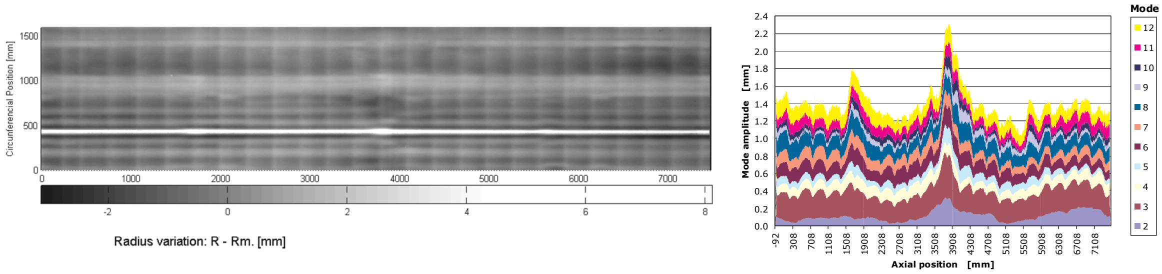

Figure 5. Pipe 1 Surface map and Fourier decomposition

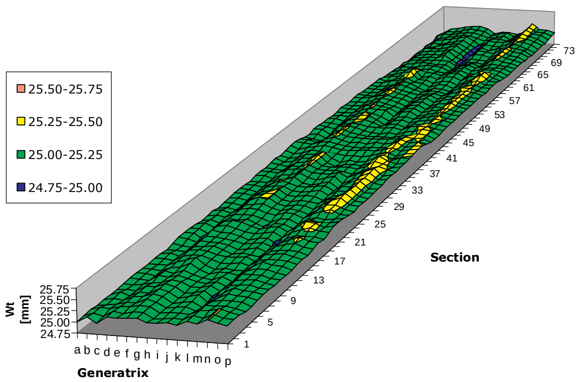

Figure 6. Pipe 1 Thickness map

Additional measurements of diameter and wall thickness were made at C-FER on each of the full-scale collapse test pipes. These results are summarized in Table 3.

Table 3. C-FER Geometric Measurements Results (Average Values)

Pipe	OD (mm)	Wall Thickness (mm)	$Ovality = \frac{(OD_{max} - OD_{min})}{OD_{nom}} x100\%$
1	507.6	25.14	0.12
2	508.0	25.19	0.19
3	507.6	25.13	0.14
4	507.2	25.01	0.26

4. Coupons preparations

120 coupon test were performed at Tenaris own lab and 160 coupon tests were performed at C-FER, summing up a total of 280 for this project. The intent was to position the coupons as close as possible to the ID and OD of the pipe while still obtaining full coupon geometry. Figure 7 shows the selected ID and OD positions for hoop and axial coupons. Table 4 presents a summary of the coupons fabricated.

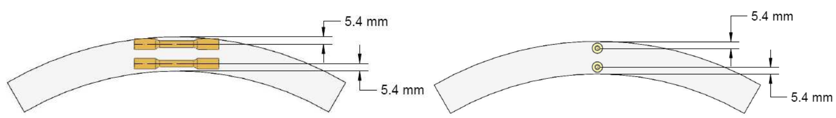

Figure 7. Hoop and Axial Coupon Positions

Table 4. Coupon Test Matrix

Lab	Coupon Source	Comments	Polar Location With Respect to Seam Weld	Axial				Hoop				Quantity Sub-total
				Compression		Tension		Compression		Tension		
				OD*	ID*	OD*	ID*	OD*	ID*	OD*	ID*	
C-FER	Pipe 1		180°	1	1	1	1	1	1	1	1	8
	Pipe 2		180°	1	1	1	1	1	1	1	1	8
	Pipe 3		45°					1	1	1	1	4
			90°					1	1	1	1	4
			135°					1	1	1	1	4
			180°	1	1	1	1	1	1	1	1	8
		Through-thickness Tests**		10		10		10		10		40
	UO Pipe 3		45°					2	2	2	2	8
			90°					2	2	2	2	8
			135°					2	2	2	2	8
			180°					2	2	2	2	8
	Plate Pipe 3		n/a	2	2	2	2	2	2	2	2	16
	Plate Pipe 3	Bauschinger Tests***	n/a					1	1	1	1	4
	Pipe 4 Before Thermal Treatment		180°	1	1	1	1	1	1	1	1	8
		One coupon-scale thermal cycle to 240℃	180°	1	1	1	1	1	1	1	1	8
		Two coupon-scale thermal cycles to 240℃	180°	1	1	1	1	1	1	1	1	8
	Pipe 4 After Thermal Treatment		180°	1	1	1	1	1	1	1	1	8
Tenaris	Plate Pipe 1		n/a							3	3	6
	Pipe 1		180°							3	3	6
	Plate Pipe 3		n/a			6	6			6	6	24
	Pipe 3		45°							6	6	12
			90°							6	6	12
			135°							6	6	12
			180°			6	6			6	6	24
			HAZ			3	3					6
			Weld			3	3					6
	Plate Pipe 4		n/a							3	3	6
	Pipe 4		180°							3	3	6
											Quantity Total:	280

* ID coupons centred 5.4 mm from ID surface. OD coupons centred 5.4 mm from OD surface.
** Coupons locations spaced evenly through the wall thickness.
*** Coupons tested by straining to 0.5% followed by testing in the opposite direction.

4.1. Coupon Scale Thermal Treatment

Coupon scale thermal treatment involved heating 16 coupons to a temperature of 240°C for 3 minutes, followed by 1 minute of air cooling prior to water quenching. Eight of the sixteen coupons were then subjected to a second thermal cycle consisting of heating to 240°C, holding for 3 minutes, and water quenching. To facilitate uniform thermal treatment, the coupons were initially machined as plain cylinders. After completion of the thermal coating simulations, these cylinders were machined to final coupon dimensions.

5. Coupons results

5.1. Plate property variation

Figure 8 shows the yield stress obtained from the coupons taken from the original plates corresponding to pipes 1, 3 and 4. As expected, the differences between the internal and external sides of the plates (corresponding to the ID and OD in the formed pipe, respectively) are very low. However there is difference of approximately 6% between pipe 1 and pipe 3 and 10% between pipes 4 and 3. Note that yield strength for this paper is defined as the stress at 0.5% strain.

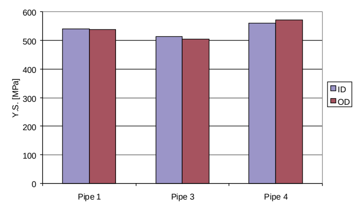

Figure 8. Yield Stress from Original Plates

5.2. Through thickness property variation

Coupons were taken through the wall thickness of Pipe 3 at the 180° circumferential location to determine variability in the yield strength with respect to wall thickness. The distribution of hoop coupons through the pipe wall and the results of the through-thickness testing are provided in Figure 9. A similar distribution was used for the axial coupons. Coupons were subsequently tested in both tension and compression.

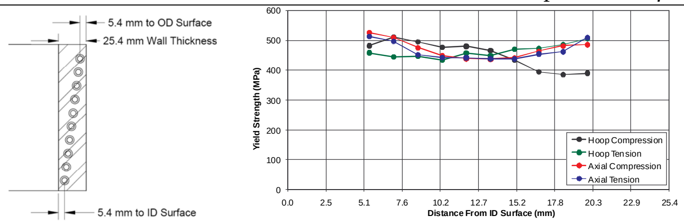

Figure 9. Through-thickness Hoop Coupon Locations and Yield Strength Variation

The axial and hoop tensile yield strengths have similar distributions, with a maximum at the inner and outer surfaces and at a minimum at the mid-wall thickness. The increasing tensile yield strength from inner to outer diameter is indicative of the effect of the forming process on the hoop direction properties. Likewise, the corresponding decreasing compressive yield strength suggests the influence of the Bauschinger effect on material properties.

5.3. Pipe Forming

Pipe 3 coupons were tested from the plate, UO, and UOE material to ascertain the influence of the forming process on yield strength. Coupons were taken from both the ID and OD locations in the hoop direction and were tested in tension and compression. The results of the tests are shown in Figure 10.

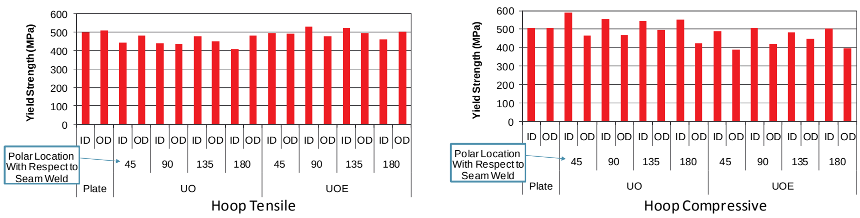

Figure 10. Forming Effects on Hoop Tensile and Compressive Yield Strength

Comparing the UOE to the UO results, the hoop compressive yield strength decreased while the hoop tensile strength increased. Additionally, the hoop compressive yield strength of the ID coupons was greater than the corresponding OD coupons for both UO and UOE specimens. The decrease in compressive yield strength between the UOE and UO coupons, including the variance between ID and OD, is indicative of strain hardening and the associated Bauschinger effect on the material properties due to the forming process.

Tension and compression tests were also conducted on axial coupons taken from the plate and UOE samples associated with Pipe 3. As shown in Figure 11, there was an increase in tensile yield strength between plate and UOE specimens.

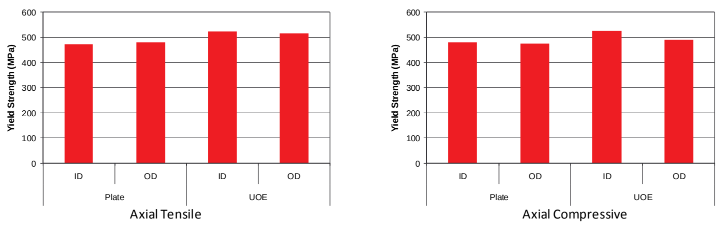

Figure 11. Forming Effects on Axial Tensile and Compressive Yield Strength

5.4. Thermal Treatment

A thermal-treatment study was completed using Pipe 4 to evaluate the effect of mild heat treatment, simulating the thermal cycle associated with a typical fusion-bond epoxy coating process, on tensile and compressive stress-strain behaviour. Samples were taken from Pipe 4 before and after full-scale thermal treatment. Coupon-scale thermal treatments were performed on some of the samples that were not subjected to the full-scale thermal treatment. The goal was to determine the effect of thermal treatment on yield strength and stress-strain curve shape. Coupons were taken from near the ID and OD, in the axial and hoop directions, and from an orientation of 180° with respect to the weld seam. These coupons were then tested in both tension and compression. The compression test results for the hoop direction are shown in Figure 12.

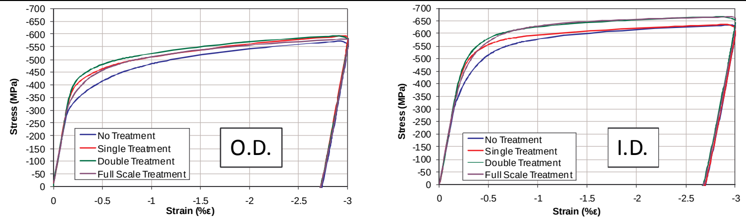

Figure 12. Compression Test Results for OD and ID Hoop Thermal Treatment Coupons

As can be seen in Figure 12, there is a progressive increase in yield strength between the no treatment ("as-received"), single treatment and double treatment coupons. Of particular interest was the recovery of compressive yield strength, in the hoop direction, initially lost as a result of the UOE forming process. Additionally, the transition at yield becomes sharper indicating a recovery of material properties closer to those of its virgin form.

6. Full-Scale Test Results

Figure 13 shows the results of the collapse and the subsequent buckle propagation test for Pipe 2 together with a photograph of the collapsed pipe. The collapsed specimen appearance and plots are typical for all four collapse and propagation tests.

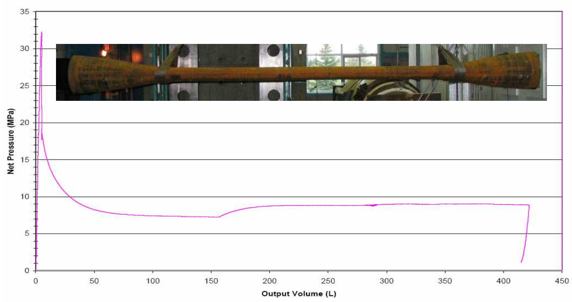

Figure 13. Pipe 2 Collapse and Buckle Propagation Test and Specimen After Collapse

Table 5 summarizes collapse and propagation pressure of each pipe along with the UOE forming parameters.

Table 5. Collapse Result Summary

Pipe	Compression Ratio (%)	Expansion Ratio (%)	Forming Ratio (ER-CR)	Collapse Pressure (MPa)	Propagation Pressure (MPa)
1	0.20	0.55	0.35	34.4	8.9
2	0.47	0.86	0.40	32.2	8.9
3	0.61	0.85	0.24	33.2	8.9
4	0.16	0.77	0.61	43.0	9.7

Figure 14 shows the collapse pressure against the forming ratio (left) and the collapse pressure normalized by the yield stress obtained from original plates (right).

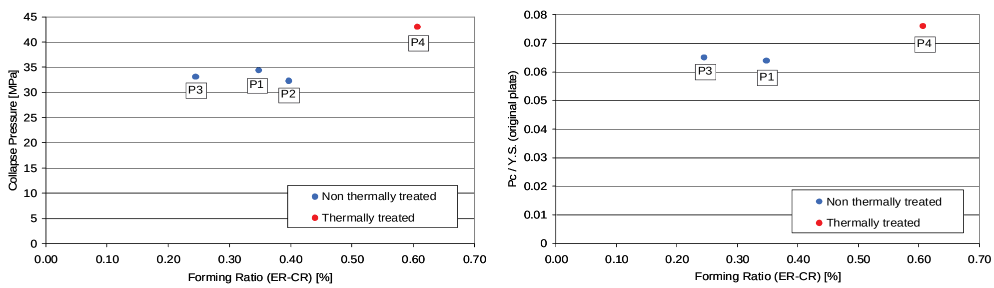

Figure 14. Collapse Pressure and Normalized Collapse Pressure against Forming Ratio.

It can be seen in the normalized graph that pipe 3 increased its value relative to pipe 1 due to a lower yield stress in the original plate. Unfortunately, the yield stress for plate 2 could not be obtained to complete the second graph. Although we do not have this point, the results of the non-thermally treated pipes (1 and 3) show a tendency to decrease collapse resistance as forming ratio increases. Even though its forming ratio was higher, the thermally-treated pipe (Pipe 4) collapsed at a pressure 29% higher than the average of the other three pipes showing a significant influence of the heat treatment on the collapse resistance of the pipe.

The compression test results, for coupons taken from the pipe ID and OD in the hoop direction, only yielded an average increase of 11% between the thermally-treated pipe specimens and the corresponding average of specimens from the other three pipes. All these results are consistent with the results of previous work done at C-FER [5-8].

7. Summary and conclusions

A multi-phase research program at Tenaris' research facility in Argentina to model the UOE pipe manufacturing process has recently completed one of its milestone efforts involving full-scale testing of controlled-fabrication UOE linepipe. This phase of work offered the unique opportunity to better understand UOE pipe material during various stages of manufacture (plate to UO pipe to UOE pipe to heat-treated UOE pipe). The results presented in this paper have provided a substantial increase in understanding the interaction between the UOE manufacturing process and material properties.

Presented work included numerous material property tests at various stages of manufacture, full-scale collapse and buckle propagation tests, and in-depth thermal-treatment studies on the influence of a mild heat treatment on collapse strength. Some influence of the forming parameters on collapse pressure was shown, but these parameters do not seem to influence the propagation pressure for the cases considered. On the other hand, a mild heat treatment was observed to significantly increase the collapse resistance of the pipe.

The research program will be entering its next phase of work, which involves enhancing the FEA model used to predict collapse and obtaining a better understanding of the influence of the UOE forming parameters on collapse strength. It is possible that these parameters could be modified to increase the collapse strength of UOE linepipe intended for ultra-deepwater applications, in addition to the benefits realized from the thermal treatment associated with the fusion-bond epoxy coating process.

8. Acknowledgements

The support of Tenaris for this research program is gratefully acknowledged.

9. References

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