DEVELOPMENT OF LOW COST CARBON STEEL TUBE FOR SUGAR MILL EVAPORATORS IN SOUTH AFRICA

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Abstract

Due to the recent droughts, the retube of Sezela evaporators was delayed for a few years, resulting in a need for a low cost carbon steel tube to retube five evaporators. A recent failure highlighted the importance of the heat treatment and expansion characteristics of these tubes. This paper discusses the failure of a carbon steel tube, the development of the heat treatment of locally manufactured tubing, the expansion procedure for the tubes and other related problems with large scale vessel retubing.

Introduction

Sezela intended cascading carbon steel tubes from the 6,8 m Kestner vessels to lower order evaporators when the Kestner was to be retubed with stainless steel tubes for the 1996-97 season. However, the Kestner retube was cancelled in November 1995 and an alternative supply of carbon steel tubes had to be found. Pongola mill had used an inexpensive heat treated carbon steel tube (SAE 10/10) without problems but, due to the long delivery times (on average three months) the best that could be sourced was an SAE 10/10 carbon steel tube, without heat treatment. This was considered satisfactory at the time. (At the time of writing, these heat-treated tubes had been in service for four years at Pongola mill without a failure.)

SAE 10/10 tubing and expansion problems

Problems were experienced when expanding the SAE 10/10 tubes into the tube plates, and tubes were reportedly harder than other carbon steel tubes. After repeated re-expansion of certain tubes during the season by mill staff and contractors, it was decided to replace the tubes.

Metallurgical examination of SAE 10/10 tubes

Tube samples of SAE 10/10 were sent to the co-author (Bartholemew) at Natal University's Mechanical Engineering Department for analysis to determine the cause of failure.

A tensile test indicated that the tube was still in cold finished condition. Microscopic examinations of the electric resistance welded joint and the parent material were done. The microstructure of the parent metal of all the specimens was found to consist of slightly deformed grains of ferrite, with small areas of pearlite at the grain boundaries. The ASTM grain size number was estimated to be nine or 10. The structure of the weld was similar although finer and containing some widmanstatten ferrite. The microstructures were typical for this type of tube in the cold finished condition. Vickers hardness tests, using a 10 kg load, were performed on the microspecimens, which yielded the following results:

Parent metal : 150-152 HV
Weld metal : 202-209 HV.

Discussion

The results of the tests and examinations performed indicated that the tubes were not in a condition suitable for expanding. The tubes were in the cold finished condition and therefore exhibited yield point values that were too high and too close to the ultimate tensile strength of the material, i.e. tensile to yield ratios of 1,1 to 1,0. A more acceptable ratio would be, say, 1,7 to 1,0 (refer to Figure 1).

When the yield strength and the tensile strength are close to each other, the control required for tube expansion into the tube plate becomes unacceptably tight. This is because the tubes need to be expanded sufficiently to put the steel into the plastic range, but without encroaching on the ultimate tensile strength or, in other words, fracturing the tube end.

The second point to be discussed here is the effect of the electric resistance weld. As can be seen from the results of the hardness tests, the weldment was 50 to 60 HV points higher than the parent metal. A much higher stress would be required to permanently expand this area on the periphery of the tube.

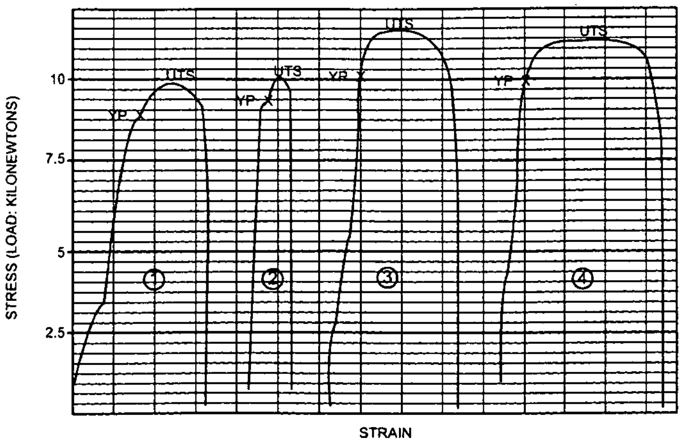

Figure 1. Stress/strain curves for SAE 10/10 tube versus Tubecon ST33 tube, both cold rolled condition. Curves 1 and 2 are SAE 10/10 and curves 3 and 4 are Tubecon. Apparatus is 500KN Avery Universal Testing Machine.

It is clear from the above that the tubes must be heat-treated as required by the tube specification, i.e. the tube must be annealed or normalised, furthermore any weld metal reinforcement must be removed prior to expanding.

Planning for 1996-97 off-crop

During the 1996-97 season, the evaporators were undergoing large scale tube failures as a result of corrosion, on the vapour side, that had taken place due to high acetic acid levels in the juice. The high level of acetic acid was a result of bad cane quality during the preceding drought years. Consequently, plans were made to retube six of the 13 evaporators.

Stainless steel 439 tubing for the 1B1 Kestner retube had been purchased at a cost of R33,00 per metre (3 043 tubes x 6 800 mm long).

- The 5B2 evaporator with the SAE 10/10 tubes required replacing (2 480 tubes x 2 225 mm long).
- Towards the end of the season, carbon steel tubes in 2A and 2B evaporators were failing at a rate of about 200 per week. (2A: 3 613 tubes x 3 505 mm long; 2B: 3 294 tubes x 3 505 mm long).
- 3A and 3B evaporators had 304 stainless steel tubes, 17 and 20 years old respectively. These tubes were snapping off at the lower tube plate and causing significant problems even though the incidence was relatively low (3A: 3 820 tubes x 2 550 mm long; 3B: 2 125 tubes x 2 090 mm long).

Table 1. Vessel and tube lengths.

Item	Vessel	Tube length (mm)	Number of tubes	Total length (m)
1	5B2	2 210	2 490	5 502,90
2	2A	3 505	3 613	12 663,57
3	2B	3 505	3 294	11 545,47
4	3A	2 550	3 830	9 766,50
5	3B	2 090	2 135	4 462,15
			15 362	43 940,59

Purchase of new tubes

Due to the large scale tube failures only becoming evident late in the year when there were budget pressures, a tender was issued with a wide range of carbon steel specifications, as listed below, that would suit evaporators.

Tenders were called for the following tube specifications:

- Specification for seamless cold drawn low carbon steel heat exchanger and condenser tubes SA-179/SA 179-M.
- Specification for seamless medium-carbon steel boiler and superheater tubes SA-210/SA-210M. Note: hot-finished tubes shall be annealed unless agreed to the contrary in writing.
- Steel boiler and superheater tubes to BS3059 Part 1 of 1987 ERW ST 320.
- BS3601: 1974 Grade 320 solid drawn normalised.
- BS3601: 1994 Grade 320 ERW / normalised.
- ASTM A450: fully annealed material ASTM A214.

Applicable standards and codes

- BS5500 Unfired pressure vessels.
- ASTM A370: Methods and definitions for mechanical testing of steel products.
- ASTM A450: Specification for general requirements for carbon, ferritic alloy and austenitic alloy steel tubes.
- ASTM E246: Electro-magnetic (eddy current) testing of tubes and welded tubular products, austenitic stainless steel and similar alloys.
- ASTM A763: Intercrystalline corrosion testing.

Table 2 refers to the schedule of different materials, cost per metre, delivery and source. Delivery was a critical factor as budgets were only approved late in the year.

Evaluation of offers

Table 2. Analysis of tender tube prices received and delivery (November 1996 prices).

Item	Specification : Low carbon steel	Cost per metre	Delivery	Import/local
1	BS 3059 PTII steel 320 w/out heat treatment (2,5 mm WT)	R12,84	on time	local
2	(1) with heat treatment	R17,09 (R14,97)	on time	local
3	ASTM A179/A 450 seamless (2 mm)	R21,81	late	?
4	ASME SA 210 GRI 2,6 mm	R22,13	14 weeks late	import
5	BS 3059 PTI 3,25 mm	R33,50	late	?
6	SAE 10/10 NS 94	R18,78	late	?
7	ASTM 179/A450 2 mm	R27,20	late	?
8	ASTM 179/A450 stainless steel, 50,8 x 1,2 wall thickness	R22,25	late	import
	a] 304L ss	R31,36 to R47,39	late	import
	b] 439 ss	R33,00	late	import

Tubecon was selected as a potential supplier, subject to verification of the material certification and a visit to their works to determine their capability of handling 44 000 metres of tubing. Early budget approval was sought to ensure that Tubecon could place an order with ISCOR for the supply of sufficient quantities of cold rolled plate. Due to large quantity and long delivery times, Tubecon could not undertake the heat treatment so it was decided to handle this in-house. The tube supplier agent offered ends annealed at Sezela at a cost of R68 000. After detailed discussion with them and the co-author, it was decided to heat treat complete tubes at Elgin Works in Durban. Ends only annealed would result in a transition phase between the cold rolled and annealed section that could result in an area highly susceptible to corrosion.

Establishing the heat treatment procedure

The aim of annealing the tubes was to produce a ductile tube for effective expansion with a uniform grain structure. The higher the heat soak temperature the better the result would be, but the more tube distortion and scale build-up on the external surface of the tube. This would result in difficulty in installing tubes and adversely affect the heat transfer rate.

A brief review of the basic metallurgy of hypoeutectoid plain-carbon steels

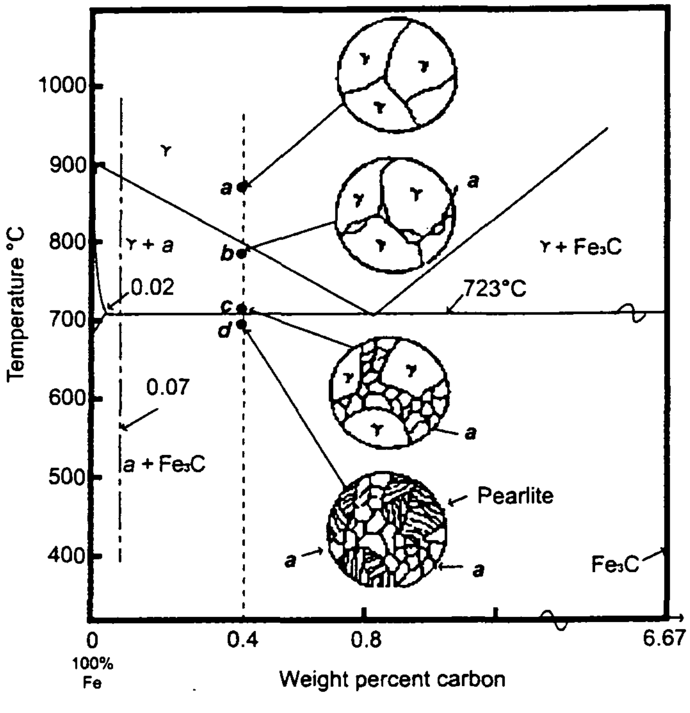

Figure 2. Transformation of a 0,4% carbon hypoeutectoid plain-carbon steel with slow cooling, with 0,07 carbon shown typical of the tubes used.

If a sample of a 0,4% plain-carbon steel (hypoeutectoid steel) is heated to about 900°C (point *a* in Figure 2) for a sufficient time, its structure will become homogenous austenite. If this steel is then slowly cooled to the temperature shown at point *b* in Figure 2 (about 775°C), proeutectoid ferrite will begin to nucleate heterogeneously at the austenite grain boundaries. As the alloy is continuously cooled from the temperature at point *b* to that at *c* in Figure 2, the proeutectoid ferrite will continue to grow into the austenite until about 50% of the sample is transformed. The excess carbon from the ferrite that is formed will be rejected at the austenite-ferrite interface into the remaining austenite, which becomes richer in carbon.

While the alloy is cooled from the temperature at point *b* to that at *c*, the carbon content of the remaining austenite will be increased from 0,4 to 0,8%. At 723°C, if conditions approaching equilibrium prevail, the remaining austenite will be converted to pearlite by the eutectoid reaction.

Continuous-cooling transformation for a hypoeutectoid plain-carbon steel

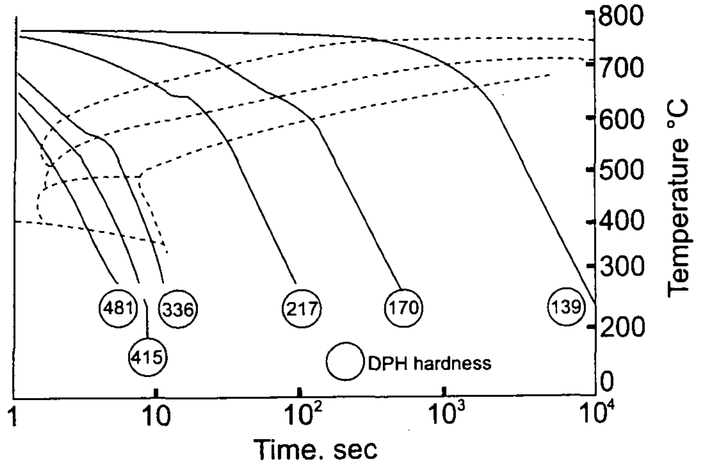

Figure 3. *(a)* continuous-cooling diagram for 0,3% plain-carbon steel (0,70% Mn, 0,25% Si). The isothermal diagram for the steel is shown in dashed lines. *(b)* C-T diagram with selected cooling rates decreasing from left to right. Diamond pyramid hardness (DPH) values are indicated inside circles for each cooling curve.

Cooling at the slowest rate indicated by the curve with the DPH value of 139 produces the softest structure, which is a mixture of proeutectoid ferrite and pearlite in almost equal amounts. This structure is similar to that obtained by slow (furnace) cooling this type of steel. Increasing the cooling rate slightly produces finer pearlite and slightly less ferrite, with the hardness increasing. Increasing the cooling rate still further drastically reduces the amount of proeutectoid ferrite that now outlines the former austenitic grain boundaries. Increasing the cooling rate still further causes a split transformation to occur. The rate of cooling is so fast that very little proeutectoid ferrite is formed. Instead, pearlite outlines the former austenitic grain boundaries. Some bainite is formed, and martensite was formed when some of the austenite remained untransformed. Increasing the cooling rate even more increases the amount of martensite formed, and still gives a split transformation. Some proeutectoid ferrite and pearlite are formed at the former austenitic grain boundaries. Small amounts of acicular bainite were also formed. Note that the hardness of the sample increased markedly due to the large percentage of martensite. Finally, the last structure is almost completely martensitic.

Annealing and normalising plain-carbon steels

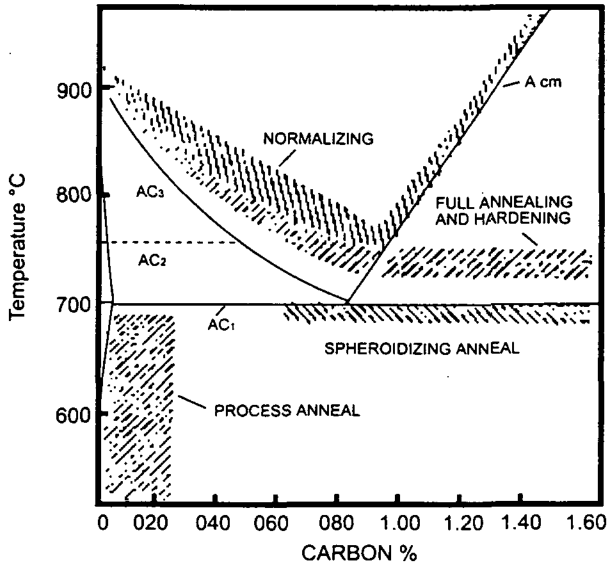

Figure 4. Commonly used temperature ranges for annealing plain-carbon steels (after Digges *et al.*, 1966).

Most useful engineering alloys must possess an appropriate combination of strength and ductility. Ductility in metals and alloys allows them to be deformed plastically by various fabrication processes into the desired shape, without fracturing. During plastic deformation or cold working, the main reason for the increase in strength is due to the increased generation and rearrangement of dislocations. In order to make cold-worked metals ductile, they are annealed at appropriate temperatures. During annealing, the highly distorted cold-worked structure is partly or completely returned to a softer, more ductile structure containing fewer dislocations. The two most common types of annealing processes that are applied to commercial steel are *full annealing* and *process annealing*.

Microstructural changes that occur during annealing

During annealing the changes in microstructure that occur can be subdivided into the following major processes:

- *Recovery*. In this process, the cold-worked metal is heated to the required temperature so that dislocations can be arranged into lower-energy configurations.
- *Recrystallisation*. When a cold-worked metal is heated to a high enough temperature, termed the 're-crystallisation temperature', new strain-free grains are formed by the migration of large-angle boundaries of high mobility.
- *Grain growth*. Continued annealing of a recrystallised structure promotes the formation of a more stable grain structure. In this process, larger grains grow at the expense of the smaller ones.

Selection of most appropriate heat treatment specification

The co-author (Bartholemew) proposed a number of heat treatment procedures for tubes to be supplied to Sezela. As can be seen from the brief discussion on the heat treatment of low carbon steels there was a need to do actual furnace trials at Natal University to determine the most effective procedure. Sample lengths of the tube were obtained and subjected to predetermined heat-treatment cycles as follows:

Normalised : 900 - 920°C
Annealed : 910 - 930°C
Tempered : 590 - 610°C
Sub-critical annealed (Spheroidised) : 680 - 720°C.

On completion of heat-treatment, tensile test specimens were machined and tested. In addition to these, one specimen in the as-received (cold-finished) condition was prepared.

Table 3. Analysis of different heat treatments.

Description	Heat soak temp (°C)	Hold time (hours)	Cooling	Yield stress (MPa)	Ultimate tensile stress (MPa)	Elongation (%)
At University of Natal						
As received – no heat treatment, i.e. cold finished	–	–	–	352,4	412,7	17,4
Normalised	900-920	one	air	249,2	335,4	32,2
Annealed	920	two	furnace	235,7	309,8	30,0
Tempered	600	one	air	323,1	381,5	33,0
Sub-critical anneal (spheroidised)	700	two	furnace	308,9	374,0	39,4
Sub-critical anneal (spheroidised)	700	three	air	241,3	354,6	24,4
At Elgin Works	710-730	three	Air	292,0	371,3	27,8
	690-710	two	Air	308,5	375,0	25,3
SAE 10/10 Network, not heat treated	–	–	–	365,0	400,0	18,8
ST320 – Tubecon, not heat treated	–	–	–	324,1	374,7	31,2

Note: Elongation (%) describes the extent to which the specimen stretches before fracture.

Results obtained from these tests indicated that normalising at 920°C would be the most acceptable treatment. However, primarily because of the economic implications and the danger of distortion, it was decided to modify the subcritical anneal cycle to determine whether a workable result could be obtained at a lower temperature. Two further tests were processed:

- Sub-critical anneal (spheroidised): 690°C for three hours, followed by air cooling
- Sub-critical anneal (spheroidised): 690-710°C for three hours, followed by furnace cooling.

Discussion

The results of the tensile test performed on the as-received specimen confirmed that the tube was in the cold-finished condition. Of the first four treatments, the normalising treatment yielded the best set of results. However, the heat treatment advisor at Elgin Works expressed concern that the tubes would distort during such a cycle, since this treatment took place at the high temperature of 910°C.

If the ends were not fully annealed it would take longer to mechanically expand the tubes into the tube plate; this would increase the cost of installing the tubes in the evaporators. This being the case, the soaking time of the sub-critical anneal treatment was increased so as to ensure complete spheroidisation, thus rendering the steel in a soft, ductile condition. It was also decided to try the two forms of cooling, i.e. still-air cooling and cooling in the furnace, in the hope that the desired effect could be achieved with the quicker air cool. The difference between yield and tensile was the same, i.e. 113 MPa for the final two tests, with the tensile to yield ratios being near enough to 1,5 to 1,0. It was therefore decided to heat-treat the tubes using the following cycle:

- Heat to 710-730°C
- Hold for three hours
- Remove from furnace and cool in still air.

It was expected that the results from production heat treatment would differ from those achieved under laboratory conditions. Steps were therefore taken to monitor the heat treatment results after the first production batch was completed.

It should be pointed out here that spheroidisation of the structure, which is the transformation effect that renders the steel softer and more ductile, is not as predicatable a treatment as is normalising, which refines the grain size and homogenises the structure. In the case of sub-critical anneal, the degree of spheroidisation achieved is dependent on the holding temperature and rate of cooling, i.e. the longer the time at temperature and the slower the cooling rate, the softer and more ductile the steel. However, furnace cooling, which is part of the sub-critical annealing cycle, can often result in yield and tensile strengths which are below the minimum requirements specified for the steel and thus great care had to be taken when determining the actual cycle to be used. In addition to the acceptable tensile properties obtained, the desired reduction in the hardness of the weld was also achieved. Samples were taken after the first batch had been heat treated in the Elgin furnace and tested to monitor the effectiveness of the heat treatment. The results were in line with the laboratory test and Elgin were instructed to proceed as follows:

- Heat to 720°C (710-730°C).
- Hold for three hours
- Remove from furnace and cool in still air.

Heat treatment at Elgin Works

Elgin Works has an International Standards Organisation procedure for heat treatment, which was relied upon for consistency. To limit distortion, the furnace had to be loaded to ensure no direct flame impingement on tubes. Tubes had to be placed to get even heat distribution. Each heat treatment batch had thermocouples installed to monitor the furnace temperature of the heating and cooling processes. After the first heat treatment, a tube was sent for analysis and the results were as follows:

- Yield stress : 292 MPa
- Ultimate tensile stress : 371 MPa
- Elongation : 27,8%.

The difference between the ultimate tensile stress and the yield stress was sufficiently large to allow the mechanical expansion of the tubes into the tube plates without posing any problems (refer also to Table 3). Since the results were acceptable the tubes were delivered direct from the tube mill to Elgin Works for heat treatment. To straighten bent tubes a simple two-man press was used. To remove the scale a trommel was designed using an old 800 mm steam pipe, mounted on four trolley wheels and driven by a motor, gearbox and rubber wheel.

Essential aspects of quality control

- Full chemical analysis and tensile test should be done on final tubes delivered to site.
- Each bundle of tubes to be traceable from the tube mill to site with the relevant manufacturers' certificates, tube mill test certificates and heat treatment certificates.
- Test samples to be supplied attached to relevant tube bundles, i.e. flare and flattening tests.
- Establish a claims procedure or penalty system in the contract with the heat treatment company and tube mill for out of specification tubes, i.e. bent due to heat treatment or weld failures, or oversize tubes.
- Check the required tube length in the vessel at least twice before final order is placed as tube plates could have moved since the original drawing.
- Support large tube plates in the centre when installing new tubes to prevent sagging.
- Establish a tube expansion procedure and a quality plan to ensure the tube expansion procedure is followed.

- Make sure copies of the standards to which tubes are to be manufactured, heat treated and installed are available, read and understood by all parties.
- Do not start tube removal until tubes are manufactured and accepted with respect to quality, or tubes have landed in the country.

Analysis of tube cost

The final tube cost was R14,97 per metre delivered to site. Sezela had budgeted R21,00 per metre; the next acceptable price was R22,13; this gave a saving of R7,16 per metre or R313 318,00 on the retube programme. This saving allowed one additional retube, which was not budgeted for.

Table 4. Summary of final tube costs.

Tube analyses – University	7 350,00
Cooperheat inspection at Tubecon Mill	10 808,00
Heat treatment at Elgin	55 200,00
Transport from Elgin to site	10 000,00
Test plates for expansion	6 900,00
Tube manufacture	564 688,31
Total tube cost	R654 946,31
÷ Total tube length (m)	43 756,49
Cost per metre	R14,97

Had 439 stainless steel been used at R33,00 per meter, tube cost would have been R1 443 964,17. The labour cost to retube the vessels (excluding the cost of the tube itself) was between R32,00 and R49,00 per tube, depending on the contractor's rate. All the above are at January 1997 prices.

Cost comparison between carbon steel and stainless steel evaporator tubes

Because of the large number of retubes required, and due to a tight budget, carbon steel tubes were used. A cost comparison over the long term showed that stainless steel tubes are at least 45% less expensive, and at best 78% less expensive than carbon steel tubes, depending on whether the carbon steel tubes are re-used in shorter tube length vessels (Appendix 1). Stainless steel tubes can have a life of about 17 to 21 years depending on damage done by *skato skalo* mechanical cleaning. Carbon steel tubes have a life of about four to seven years at Sezela, and if tubes are re-used in other shorter tube length vessels, tube life can be extended to 14 to 15 years.

Conclusion

Carbon steel tubes in the cold finished condition can be heat-treated to a condition such that they are suitable for expansion into the tube plate. This course of action is usually only required if, for example, there is a late season failure of evaporator tubes, or perhaps a limited budget. For the whole process to be successful the tube mill must be inspected to ensure that the steel grade complies with specification and that the mill's quality control is adequate to manufacture to the desired specifications. The heat-treatment procedure must be carefully worked out and tested both in the laboratory and in production.

If, however, there is sufficient budget and time is available the correct grade of stainless steel should be considered because in the long term, stainless steel tubes are cheaper than carbon steel tubes.

Acknowledgements

The author would like to thank John Field for his support and Sezela mill staff for their effort in this project.

REFERENCE

Digges, TG *et al* (1966). Heat treatment and properties of iron and steel. p 10 In: NBS Monograph 88.

APPENDIX 1

Cost comparison between carbon steel and stainless steel evaporator tubes.

Sezela has 13 evaporator vessels with an average of 3 425 tubes per vessel and an average tube length of 3 915 mm.

- Assume a life of 20 years for stainless steel.
- Stainless steel tubes cost R33,00/m.
- Cost to fit a tube was R45,00.
- Assume an average life of carbon steel of 6,7 years.
- Three retubes in carbon steel would give an average life of 20 years.
- Cost to remove and replace a tube was R45,00.

Stainless steel tubes over 20 years

Tube cost 3 425 tubes x 3,915 m/tube x R33,00/m	R442 493,00
Labour cost 3 425 tubes x R45,00/tube	R154 125,00
Total for stainless steel	R596 617,00

Carbon steel tubes over 20 years
(re-using tubes only once)

Tube cost 3 425 tubes x3,915 m/tube x R14,97/m x2 (one set re-used m/s + 2 sets new m/s tubes)	R401 462,00
Labour cost 3 425 tubes x R45,00/tube x 3	R462 375,00
Total for carbon steel	R863 837,00
Difference (carbon steel – stainless steel totals)	R267 220,00
% difference (carbon steel – stainless steel totals)	45%

Carbon steel tubes over 20 years
(using tubes only once)

Tube cost 3 425 tubes x3,915 m/tube xR14,97/m x3	R602 193,00
Labour cost 3 425 tubes x R45,00/tube x 3	R462 375,00
Total for carbon steel	R1 064 568,00
Difference (carbon steel – stainless steel totals)	R467 951,00
% difference (carbon steel – stainless steel totals)	78%