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THIN-WALL TITANIUM CONDENSER TUBING

THE NEXT PLATEAU

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ABSTRACT:

Commercially pure (cp.) titanium and its alloys provide excellent resistance to general and localized corrosion attack under most oxidizing, neutral and inhibited reducing conditions in aqueous environments. Titanium is also notable for its outstanding resistance to chlorides and other halides generally present in most process streams. In addition, titanium resists other malicious phenomenon including steam and particle erosion, crevice corrosion, galvanic attack and MIC. Given this general corrosion immunity, designers have increasingly applied thin-wall condenser tubing in pursuit of cost savings and performance enhancement.

Typically, these thin-wall applications have, over the past several years, been limited to 25 BWG or 0.020"/0.5mm walls or heavier. The "industry" has, out of necessity, moved to address the special nuances of the 25 BWG including design, procurement, handling, fabrication and testing parameters with increasing success. It would appear however, that designers, operators and pundits alike require further education and refinement on the specific operational characteristics when integrated into the powerplant environment.

Considerable work has been recently completed investigating even thinner wall titanium tubing. This paper will address the essential data elements of this expanded research focusing specifically on Grade 2 titanium in 27 BWG or 0.016"/0.4mm. Since a significant portfolio of 27 BWG installations is rapidly taking shape, it is prudent to examine key ingredients that would warrant consideration of this "next-plateau" gauge material. Indeed, work is currently underway exploring the technology required to fabricate condenser tubes as thin as 30 BWG /0.013"/0.3 mm.

In summary, the paper will present and summarize substantive evidence suitable for comparison against previously acquired empirical data and prior art.

BACKGROUND

Previous work, completed during the mid 90's and published in 1999 [1, 2, 6, 7], suggested the properties of thin-wall titanium could provide attractive options to the designer/user in terms of habitat suitability, long-term reliability and performance and economic savings.

Empirical and actual testing was used at that time to compare the prevailing wisdom of heavier wall tubing usage vs. the newly introduced thin-wall.

Actual testing involving fatigue properties, both from internal pressure and external excitation, demonstrated highly admirable characteristics. Buckling strength or longitudinal compression tests were evaluated employing Euler's equations and found to be well within acceptable limits [1,6]. Other key issues including mechanical expansion and resultant pullout strengths were compared against heavier wall tubing. The results suggested a rolled and welded joint should be employed when considering tube walls less than 22 BWG/0.028./0.7mm. This procedure is highly recommended for both solid and clad tubesheets. Support plate spacing was evaluated employing steam-loading calculations applied to design base, bundle out of service and turbine bypass conditions.

Data is now available which can directly compare the previous papers' investigations and findings [l] against more mature, practical and demonstrable findings. In addition, the installation experience at the time of the paper's presentation, which was limited to several installations in Japan and Europe plus a host of desalination units, was considered inadequate.

PULL-OUT LOADS

One of the most important elements of this paper's investigation is a comparison and confirmation of the suitability, or lack thereof, of tube-to-tubesheet loads in a commercially repeatable environment using the 27 BWG tubing. Previous testing, completed in 1999 (Figure 1), confirmed that pullout loads, employing a mechanically expanded joint alone, were not sufficient to support the necessary safety factors required by the designer. However, when tube welding was added to supplement the rolled-only joint, acceptable pullout loads resulted. The tube parameters identified in the below Table 1 were used to develop the Figure 1 results.

TABLE 1

Tube Material	Titanium Gr. 2 B-338
Tubesheet Material	Titanium Gr. 2 B-265
Tube Size	1"/25.4mm
Drill-Out Hole	1.1"/28mm
Tubesheet Hole	Plain - No Serrations
Joint Configuration	Mech Exp or Exp & Weld

Additional pullout testing was recently completed which, when evaluated, could be directly compared against results reported in the previous work. In this case, this new testing was completed using the three, expansion/weld processes identified in Table 2 and tube/tubesheet parameters noted in Table 3.

TABLE 2

TEST NO	PROCESS
1	MECHANICAL EXPANSION
2	MECH EXP + ID GROOVE ASSISTANCE
3	MECH EXP + TIG WLD. (NO ID GROOVE)

TABLE 3

Tube Material	Titanium Gr. 2 B-338
Tubesheet Material	Titanium Gr. 2 B-265
Tube Size - OD & BWG	.866"/22mm x .016'/0.4mm
Drill-Out Hole	.875"/22.225mm
Tubesheet Hole	See Table 2
Joint Configuration	See Table 2

It is clear, upon examination of the new data scatter in Figure 2[3], that pullout loads are comparable to the results demonstrated in the previous 1999 work. This data similarity is not surprising and suggests practical and achievable results in a manufacturing environment.

TUBE-TO-TUBESHEET EXPANSION

Five-roll, mechanical expansion of the 27 BWG/0.016"/0.4mm thin wall titanium tube should range from 7 to 12% wall reduction. The following classic formula should be used when calculating the per-cent wall reduction.

$$\text{\% Wall Reduction} = \frac{D - (DE - 2T)}{2T}$$

where D = Hole Diameter
DE = Inner Tube Dia. after Expansion
T = Tube Wall

1. Nominal tube expansion should not exceed the tube OD by 3%.
2. Five (5) roll expanders are recommended where the OD/T ratio is greater than 25 [8].

where OD = Nominal tube OD
T = Wall thickness

Expansion beyond the upper limit may actually reduce pullout loads and potentially, induce tube cracking or incipient failure of the mechanical joint. In fact, historical results employing heavier wall tubing suggest the percent expansion need not be as high as the thin-wall counterparts - less than 10%.

TUBESHEET & SUPPORT PLATES

Particular care must be paid to the fit and finish of the drilled tubesheet plate holes. When considering thin wall titanium, this author suggests tubesheets be drilled to TEMA Close Fit Tolerance. This operation prevents excessive tube-to-tubehole clearance, which may induce undesirable tube deformation during the rolling operation.

ID groove assistance employing multiple serrations or concentric rings clearly enhances pullout strength. Serrations to a depth of 0.004"/.1mm or less are typical. Others prefer ID surface enhancement or controlled roughness (< 50 microns R_z) to achieve the desired results. What is ultimately used to enhance pullout and sealing should be left to the discretion of the designer based on actual testing and results.

Support plates should be drilled to HEI standards and deburred or chamfered on both sides of the plate. Indeed, wire brush operations may not suffice in terms of complete removal of chip material left behind after drill bit exit. This "both sides" operation is strongly suggested to eliminate or at least minimize any scratches or "exit wounds" that could be imparted to the tube OD. It is presumptuous to assume that support plate orientation during cage assembly will segregate all one-sided drilled plates in the direction of tube entry. Hoping the tube bullet will break any burr on the un-chamfered side is a bold assumption indeed and could result in unanticipated problems associated with subsequent base line E-C or other post-assembly testing.

TUBE-TO-TUBESHEET WELDING

Tube-to-tubesheet welding, employing a TIG process with shielding gas, is strongly recommended when using thin-wall tubing (under 22 BWG/0.028"/0.7mm) and solid titanium tubesheets. It is imperative when employed in a clad or bi-metallic tubesheet arrangement. Be advised that titanium can only be welded to titanium - no other commercially available material is metallurigically compatible.

Increasing the tube protrusion beyond the face of the tubesheet and reduced weld-bead heat input to the tube-tubesheet interface may prove successful in enhancing the nugget configuration and quality. However, these operations may influence weld speed resulting in increased tube-to-tubesheet weld time. Understand the thinner the tube wall, the more the tubesheet will become an ever-larger heat sink. In addition, the more the tube wall is reduced, the higher degree of difficulty in repairing the weld.

VIBRATION

Operational nuances, not normally encountered with more traditional designs, may come into play more often when evaluating the use of thin wall titanium. These phenomenon are deserving of special consideration by the designers and would include, but not limited to, the following.

Peripheral Tubes
Heavier walled tubes, typically reserved as "optional" or for the first several rows only, may require a deeper bundle penetration.

Larger OD Tubes
The use of 1"/25.4mm or larger tubes may reduce the vibration potential.

Flow Induced Vibration
Steam flow may penetrate deeper into the bundle requiring close examination of flow-induced excitation parameters.

Bundle Flow Areas
Entrance and exit areas, steam lanes, etc. in and around the bundle may have to be increased requiring additional surface area.

Support Plates
As many as one or two additional support plates may be required.

Steam bypass & bundle-out-of-service
Anomolies associated with steam bypass conditions and off-design operation will require careful "what if" scrutiny.

In terms of the support plate spacing, earlier experimental work and empirical data [(1)], concluded support plate spacing should be reduced as a ratio of tube wall vs. HEI allowable deflection. In the case of 27 BWG tubing, a ratio of .76 determined the minimum spacing to be 29". It would now appear that support plate spacing for 27 BWG tubing should fall into a range closer to the 24".

HANDLING AND LOGISTICS

To date, there is no evidence that suggests any greater degree of difficulty in handling the 27 BWG tubing vs. the heavier walled cousins. However, it is recommended that tube boxes be placed in close proximity and elevation to the bundle entry area to prevent the possibility of kinking or bending which can result from excessive tube movement. Care must be exercised to prevent any denting during the fabrication process, as this stress riser could eventually become an incipient point of high cycle fatigue failure.

Protection of the exposed tubing in high velocity and peripheral areas of the bundle must also be addressed. Dummy tubes, impingement rods and other measures must offer complete protection for the tubing from mechanical impact damage.

TUBE MANUFACTURING

Tubing produced by the supply mills to the standards of ASTM B-338 must adhere to the highest levels of quality but result in acceptable levels of mill productivity and yield. All this must take place before the condenser fabricators are convinced that the material is suitable for use in a surface condenser. Grade 2, 27 BWG titanium tubing has been successfully produced for a number of years.

Yet in terms of productivity, yields have been less than desirable. However, over the past several years, full production runs of the strip material supplied from numerous sources have proved highly successful setting the standard for commercial use.

Figure 3

Of particular significance are the low E-C (Electromagnetic or more commonly, Eddy Current Testing) & UT (Ultrasonic Testing) rejection rates for the final product. Coupled with precise control of the diameter, nugget geometry and weld-undercut discipline, users can be assured that the product will perform in a manner meeting the requirements of ASTM B-338-01a.

CLEANING

In support of actual, in-service conditions, where fouling will most certainly take place, Conco Systems of Verona Pennsylvania performed tests on sample titanium tubes manufactured to ASTM B-338 Gr. 2.

Three tests were performed on the sample material (0.9450"/24mm outside diameter (OD) x 27 BWG/0.016"AVW/0.4 mm wall thickness).

- Visual Inspection
- E-C Examination
- Hydrostatic Test

The tests were conducted using various Conco tube cleaning tools including type(s) C3S, C4S and C3X.

A visual inspection was performed comparing an as-received sample section vs. a sample section that had various tube cleaning tools "shot" or driven through. Each section was examined after the test and compared against each other. No noticeable visual or dimensional differences were discernable up to a 10X magnification.

An as-received sample was again examined using a Zetec MIZ-27 Analyzer. Only minor drift signal anomalies were recorded probably associated with the tube weld. The signals were considered insignificant. The same sample was again "shot" with the three (3) tube cleaning tools identified above. The results noted no rejectable or signals of consequence. In fact, the signals first recorded during the parent-tube test, actually reduced in magnitude after the samples were cleaned.

Finally, a third sample was hydrostatically tested to a pressure of 2100 PSI. No failures occurred noting only expected minor plastic OD deformation in the range of 0.015". In point of fact, surface condenser tubes would never experience such high pressure. Even the use of individual tube hydro testing, which operates in the range of 645 PSI, (ASME UG-27 max working pressure calculation), falls well below either the 2100 PSI or a burst pressure of a 27 BWG titanium tube (.016"/0.4mm) calculated at 3191 PSI/220 Bars.

Condenser tube fouling is real and a fact of life within an operating powerplant surface condenser. It is apparent, after reviewing the test conditions and results, that this proven type of cleaning system has no effect on the mechanical properties of the tube. If this axiom is true for scraper cleaning systems, other, more benign cleaning methods including sponge balls, brushes, water lances, etc. can be utilized with little or no apprehension.

OTHER CONSIDERATIONS

An HEI Ninth Edition Supplement, soon to be released, will address, among other issues, new criteria to be applied for steam bypass conditions. Clearly, additional work is needed by this august group beyond even this Supplement to address issues specific to combined cycle applications. Notable and unfortunate as of this writing is the absence of any HEI Standards information relating to metal resistance and/or correction factors for tubing less than 25 BWG. Designers must therefore, address the heat transfer characteristics of 27 BWG tubing independently. The thermal conductivity of titanium is readily available [8] (150 BTU/hr ft^2 - F/in) and the metal resistance can be easily developed from existing data in Figure 4.[8] should alternate rating methods be employed. Designers will find that reducing wall thickness improves the heat transfer characteristics of titanium when compared to other materials.

Reducing the wall thickness of the tubing reduces the weight of the tubing. It is noteworthy that the weight of a 27 BWG titanium tube ranges between 55 & 60% (depending on diameter) when compared to its 22 BWG counterpart.

These weight reductions and resultant uplift considerations require a more robust analysis of the foundation loads, bolting, expansion joints and other condenser components that would be impacted by the weight reduction. In addition, larger flow areas associated with thinner walled tubes can influence circulating water flow and pump NPSH considerations.

Certain conditions may preclude the complete removal of existing condenser tubes or, plant logistics make removal commercially impractical. In addition, a straight retube may prove more costly, present dissimilar material constraints and modules do not provide the required payback.

Sleeving existing condenser tubes with ultra thin wall titanium is currently under test and consideration. The thin wall is hydraulically expanded full length into the parent tube with the tube ends mechanically anchored in each tubesheet. Should additional embellishment be considered beyond just the sleeve replacement, a multi-part epoxy coating can be applied to add corrosion resistance while enhancing the tube pullout load characteristics.

INSTALLATION HISTORY

The Japanese Titanium Society reported in earlier work, [3,6,7] successful installations of 27 BWG Gr. 2 titanium in both desalination and powerplant applications. These installations have been in service for over 15 years with no documented problems. Table 4 identifies more recent vintage installations primarily in France and in the UK. It is noteworthy however, that condenser manufactures in the US are now evaluating the use of this gauge material

TABLE 4

27 BWG/.016"/0.4mm INSTALLATION LIST (Partial)

YEAR	DIM/OD	KM	DESTINATION
1981	17	5	FRANCE
1999	12.7	6	FRANCE
1999	16	12	FRANCE
1999	22	926	SPAIN
1999	24	253	GB
2001	20	7	FRANCE
2001	24	144	MALAYSIA
2001	21	288	VIETNAM
2001	24	294	GB
2002	21	137	PORTUGAL

CONCLUSION

Given continuing, industry-wide pressure to reduce costs, improve performance and significantly contribute to improved online availability and capability, a transition to less costly, high performance materials is inevitable. In the case of surface condensers employing 27 BWG or 0.016"/0.4mm tubes, the opportunity exists to examine, evaluate and realize the potential merits of reduced or thin wall tubing.

Notable in the work just presented, and a key element in this paper's investigation, is a clear confirmation of acceptable pull out loads. Welded-only tube joints, and/or welded joints employing I.D. enhancement, clearly demonstrate the repeatable practicality of achieving an acceptable tube joint within a shop manufacturing environment.

Mechanical expansion techniques, tubesheet and support plate fit & finish, tube-to-tubesheet welding and other processes appear to be successfully practiced in today's environment. They are clearly, not future technical folly but proven technology that exists today.

Efforts to address the nuances of combined cycle steam exhaust and bypass conditions will require additional work by professional societies and the manufacturers alike. Current techniques are frankly, not adequate to predict certain dangerous operating conditions.

Tube mill production runs of strip material supplied from numerous sources have produced successful yield and production goals setting the quality standard for commercial use. Handling, at both the supplier and fabricator levels, does not appear to present logistical issues nor invoke any specialized or precautionary steps.

An analysis of cleaning techniques has confirmed the future suitability of both the tube and the cleaning systems.

Recall the object of this paper, which was to evaluate additional, recently acquired data to compare, validate and expand on prior work. This author believes that practical confirmation of this work has indeed, been documented and achieved. Confirming the validity of prior art while expanding directly into newly developed technology and practical issues provides merit for future examination of thin wall titanium condenser tubing.

Figure 1

Tube Pull-Out Loads Tests - 1999

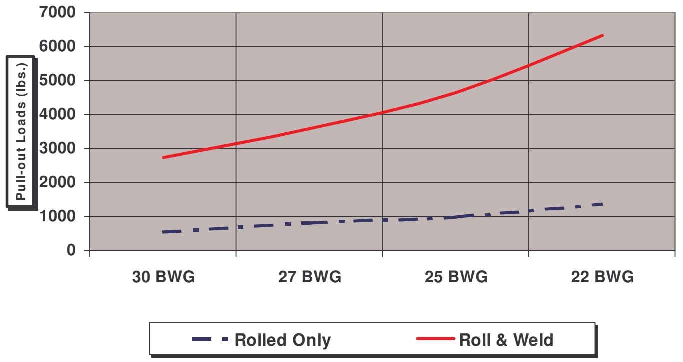

Figure 2

Tube Pull-Out Load Test - 2001

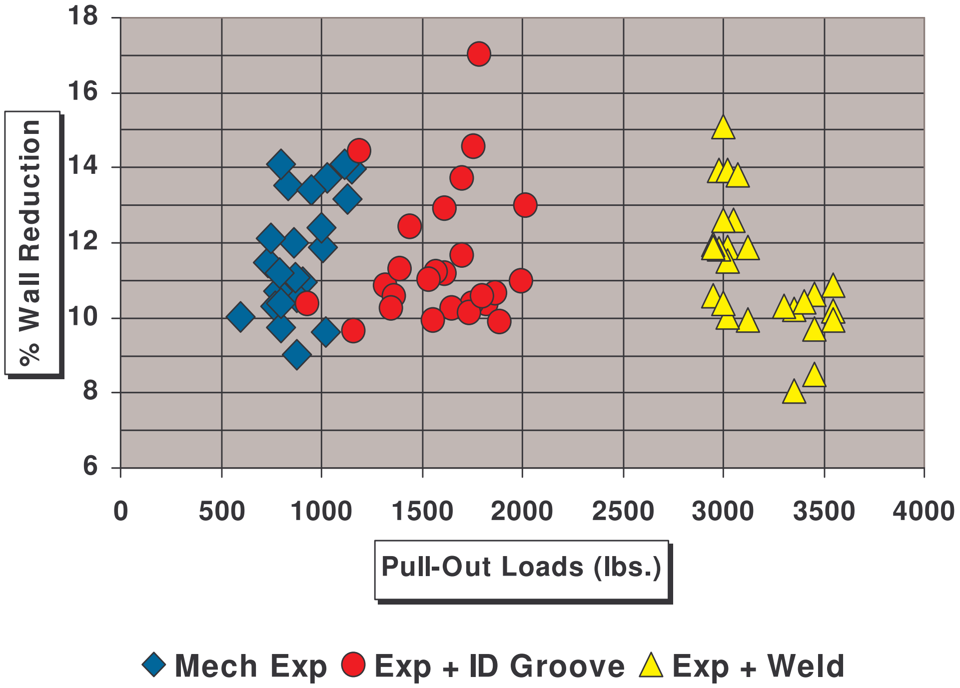

Figure 4

TITANIUM METAL RESISTANCE METAL CORRECTION FACTORS

SUPPLEMENT TO TIMET TUBE BOOK TABLE 10 - 1996 REV.

TUBE O.D IN/mm	BWG	WALL THICKNESS IN/mm	FACTOR (FM)	Metal Factor (RM)
1/25.4	25	0.020/0.508	0.95	1.3607
1/25.4	26	0.0180.457	0.96	1.2222
1/25.4	27	0.016/0.406	0.97	1.0853
1/25.4	30	0.013/0.330	0.99	0.9867
0.875/22.225	25	0.020/0.508	0.95	1.3576
0.875/22.225	26	0.018/0.457	0.96	1.2232
0.875/22.225	27	0.016/0.406	0.97	1.0878
0.875/22.225	30	0.013/0.330	0.99	0.8787
0.75/19.05	25	0.020/0.508	0.95	1.3702
0.75/19.05	26	0.018/0.457	0.96	1.2293
0.75/19.05	27	0.016/0.406	0.97	1.0908
0.75/19.05	30	0.013/0.330	0.99	0.881

Notes:

- Supplement to TIMET Tube Book Table 9 Metal Correction Factor (Fm)
- Based on 0.875" O.D. @ 7 ft/sec C@ 70^0 F
- Material = Gr. 2 Titanium
- RM (Metal Resistance) = $\frac{1 \times 10^{-4}}{\text{BTU/hr ft}^2 \ ^0\text{F}}$
- FM (Factor) Titanium Gauge Correction Factor

DMc 3/31/00

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