

## **Resistance of U-bend and Integral Finned Duplex Stainless Steel UNS-S32205 and UNS-S32750 to Sulfide Stress Corrosion Cracking**

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### **ABSTRACT**

Strain calculations, pitting resistance, and chloride stress corrosion cracking testing are currently used as the key indicators to delimit the minimum bend radius for 22% chrome duplex stainless steels without heat treatment to be 3.3 times the tube diameter for u-bend heat exchanger tubing. However, existing data does not address the limitations of this alloy, in the as cold worked condition, for sour services in the refining industry. This study evaluates the sulfide stress corrosion cracking resistance of as-bent and integrally finned 22% Cr duplex stainless steel UNS-S32205 tubing for refinery sour services by presenting hardness data and corrosion testing per ASTM G48 and NACE TM0177 of tight u-bend specimens with bend radius up to 1.5 times the tube diameter as well as integrally finned tubes. As a follow up from a previous study, the corrosion resistance of as finned 25% Cr super duplex stainless steel will also be presented.

**Keywords:** UNS-S32205, UNS-S32750, U-bending, integral finning, duplex stainless steels, pitting, sulfide stress corrosion cracking, SCC.

## INTRODUCTION

The use of Duplex Stainless Steels (DSS) in refinery sour environments is governed by ANSI/NACE MR0103/ISO 17945 NACE “Metallic materials resistant to sulfide stress cracking in corrosive petroleum refining environments” which limits DSS base materials to be used in Hydrogen Sulfide (H<sub>2</sub>S) services to a maximum hardness of 28 HRC for materials with a PREN ≤ 40 and to a maximum hardness of 32 HRC for those materials with PREN > 40.<sup>1</sup> These hardness values are in line with the hardness requirements of solution annealed as produced straight tubes, but when the heat exchanger design requires the use of integral finning or u-bend tubes, these are subject to significant work hardening that results in as bent and as finned heat exchanger tubes with hardness measurement as high as 418 HV0.5 or 35.6 HRC which clearly exceeds the allowable limits stated above.

For 22% Cr DSS integrally finned tubes to meet the hardness values as required by NACE MR0103, some end users have had to develop alternate manufacturing routes such as re-solution annealing the full length of integrally finned tubes to reestablish the hardness values to the acceptable levels.<sup>2</sup> In the case of u-bend tubes, other end users have adopted the recommendation of limiting the bend radius to 3.3D which is the equivalent to a 15% induced strain. This is done in an effort to avoid the post bend heat treatment which, when done incorrectly, can alter the duplex microstructure promoting the formation of intermetallic precipitates and affecting the corrosion resistance of the alloy.<sup>3</sup>

For 25% Cr DSS, extensive corrosion data exists that demonstrates their resistance to chloride stress corrosion cracking (SCC) for tight bend radius up to 1.5D and equivalent induced strains of 30% without the need for post bend heat treatment. Additionally, in a previous study, the authors of this paper demonstrated that despite the high hardness values resulting from the work hardening of the alloy being above the NACE MR0103 limits, DSS with PREN > 40 are resistant to sulfide stress corrosion cracking as defined by this standard.

Limited data exists in the use of DSS in the as finned and as bent condition for sour environments. This study aims to clarify if the performance of the as finned and as bent S32205 duplex tubes with hardness values above the NACE MR0103 limits is suitable for refinery sour services.

## EXPERIMENTAL PROCEDURE

### Cold Bending of Heat Exchanger Tubes:

U-bend samples were produced using seamless stainless steel tubes UNS S32205 in 0.750 OD x 0.083 inches AW ( 19.05 x 2.10 mm) and UNS S32750 in 0.750 OD x 0.065 inches AW (19.05 x 1.65 mm). The tubes were in the cold finished and bright annealed condition with chemical composition according to table 1.

**Table 1**  
**Chemical Composition of the tubes used for bending and samples for testing. All values are wt. %**

| Sample     | C     | Mn   | P     | S     | Ni   | Cr    | Mo   | N    |
|------------|-------|------|-------|-------|------|-------|------|------|
| UNS S32205 | 0.019 | 0.76 | 0.025 | 0.001 | 5.26 | 22.17 | 3.16 | 0.18 |
| UNS S32750 | 0.012 | 0.46 | 0.010 | 0.001 | 6.54 | 25.42 | 3.85 | 0.30 |

Test tubes were bent using bend dies with radii of 1.125" (28.57 mm), 1.500" (38.1 mm), and 2.250" (57.15 mm). Each representing bend radii of 1.5D, 2D, and 3D times the tube diameter of 0.750

inches(0.019 m). Post bend heat treatment for stress relief of the bend was not performed. Samples were prepared from each bend radius for hardness measurement. Each sample was cut from each bend radius tube at the center of bent section and clearly marked the position of (1) inner section of the bend (compression side), (2) outer section of bend (tension side), and (3) circumferentially between inner & outer section (neutral side).

## Tubes Finning

Using straight tubes produced from the same heat and with the same dimensions as those described in the u bending section above, integrally finned tubes were manufactured according to ASTM A1012 .<sup>4</sup> Figure 1 shows a schematic representation of the finned tube configuration.<sup>4</sup> 28 fins per inch (FPI) resulting in 0.035" fin height (FH) and 0.065 inches wall under fin thickness (WUF) were cold rolled into the tube OD for the S32205 duplex tubes as shown in Figure 2. Similarly, 28 fins per inch (FPI) resulting in 0.035inches fin height (FH) and 0.045inches wall under fin thickness (WUF) were cold rolled into the tube OD for the S32750 super duplex tubes as shown in Figure 3. These figures also demonstrate that both samples tubes maintained the same tube OD after the finning operation.

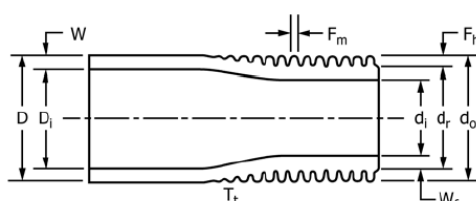


**Figure 1. Schematic of fin configuration showing the tube maintains original OD after finning operation.**

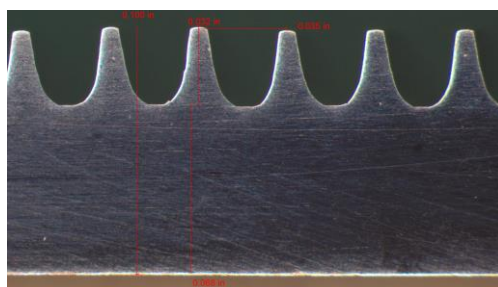


**Figure 2. Finning configuration dimensions demonstrating fin height, wall thickness under fin and tube OD for S32205 duplex tube sample.**

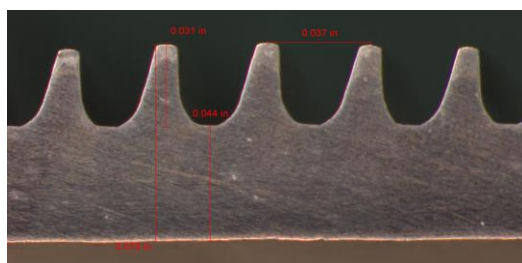


**Figure 3. Finning configuration dimensions demonstrating fin height, wall thickness under fin and tube OD for S32750 super duplex sample.**

## Hardness Measurement

### Straight Samples.

Before the bending and finning operations, the as-produced mechanical properties were recorded from Material Test Report (MTR) as seen in Table 2. Hardness testing of the straight samples was conducted using Vickers 0.5 HV scale at three different locations; sub-surface of tube OD, mid-wall, and sub-surface of tube ID. The hardness values obtained are being reported in Table 3 and the corresponding conversion to HRC scale was done for reference purposes using formula 1.

$$HRC = 0.091*HV - 2.4 \quad (1)$$

**Table 2: Mechanical Properties of as produced straight tube samples**

| Sample     | Yield Strength             | Tensile Strength           | Elongation | Hardness  |
|------------|----------------------------|----------------------------|------------|-----------|
| UNS S32205 | 96,000 psi<br>(662.1 MPa)  | 126,000 psi (869 MPa)      | 34%        | 24/26 HRC |
| UNS S32750 | 110,000 psi<br>(758.6 MPa) | 141,000 psi<br>(972.4 MPa) | 30%        | 25/24 HRC |

**Table 3**

**Micro-hardness measurement of straight tube samples and corresponding HRC conversion**

| Tube Size<br>(OD x W) | Location of<br>Measurement | Micro-<br>hardness<br>HV0.5 | Conversion<br>to<br>HRC |
|-----------------------|----------------------------|-----------------------------|-------------------------|
| S32205                | OD sub-surface             | 262                         | 21.4                    |
|                       | Mid-Wall                   | 262                         | 21.4                    |
|                       | ID sub-surface             | 262                         | 21.4                    |
| S32750                | OD sub-surface             | 282                         | 23.3                    |
|                       | Mid-Wall                   | 282                         | 22.3                    |
|                       | ID sub-surface             | 282                         | 23.3                    |

### As Bent Samples.

Samples were prepared from the as bent tubes by cutting a whole tube cross sectional area, mounting and polishing it as shown in Figure 4. Each cross section was measured at the tension point (outside of the bend with maximum tension stress), compression point (inside of the bend with maximum compression stress), and neutral point (theoretical neutral location of the bend). Additionally, each of these hardness testing locations (tension, compression and neutral) was divided into three sections: sub-surface OD, mid-wall, and sub-surface ID, as seen in Figure 5, and five hardness measurements were taken at each section using Vickers scale with a load of 500 g.

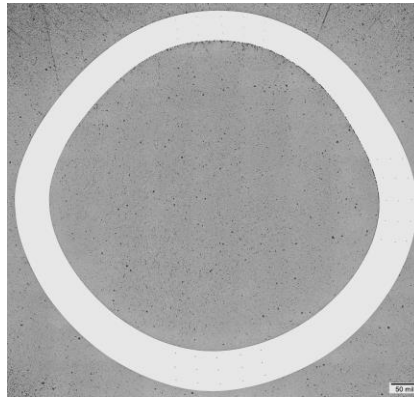


**Figure 4. Cross Sectional Area of tube mounted and polished.**

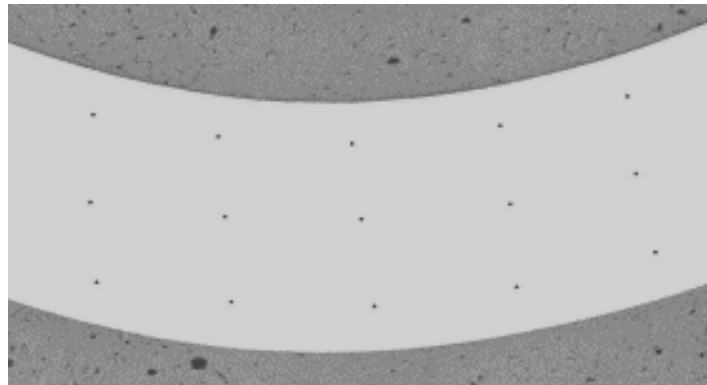


**Figure 5. micro-hardness indentation showing three sections and five measurement points per section.**

#### As Finned Samples.

One S32205 and one S32750 tube were cut longitudinally and for each sample. Five microhardness measures using Vickers 0.5V hardness scale were recorded from three locations: fin tip, mid-section of the base tube, and ID of the base tube as seen on the indentation points shown in figure 6.

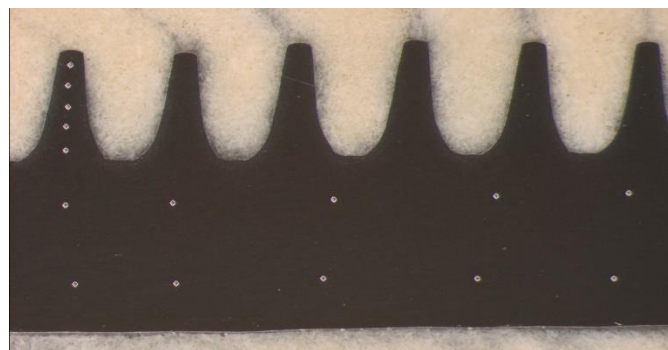


**Figure 6. Microhardness indentation of the as finned tube samples.**

#### **Pitting Corrosion Test**

Pitting corrosion testing was performed for each as bent sample and as finned sample produced in each grade according to ASTM G48 Method C. The testing parameters and acceptance criteria were defined as shown in Table XX.