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PRODUCTION PROCESS FOR HEAT EXCHANGER TUBES WITH DLC-TYPE INNER COATING

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ABSTRACT

The application of DLC-type (diamond-like carbon) coatings in shell and tube heat exchangers presents a promising solution to mitigate fouling. These coatings are favoured for their high abrasion resistance, ease of cleaning, and minimal fouling. However, the advancement of this technology is currently impeded by the absence of efficient production methods.

At the University of Applied Sciences Upper Austria in Wels (FH OOE), research is being conducted on the industrial use of DLC coatings in conjunction with shell and tube heat exchangers. This research utilizes PACVD-reactor technology (plasma-assisted chemical vapor deposition) provided by the RUBIG Group in Austria.

Two production approaches are being explored: the G-route, which involves gap-coating for elongated tubes, and the C-route, which is suited for cavity coating of shorter, individual tube segments. This paper delves into the C-route coating, specifically applied to the interior of tubes measuring 400 and 700 mm in length, with an external diameter of 25 mm and a thickness of 2 mm, composed of stainless steel alloy 1.4571/316Ti. It examines the coating's primary heat resistance. To achieve the final product length of approximately 6000 mm, orbital welding was employed. The finished products underwent testing for mechanical properties and deviations in straightness. The findings indicate that the route is highly effective, with an efficacy rate of 98 to 99% in preventing fouling in tubes of these specifications. Notably, the only areas left uncoated are those within the orbital weld zones.

INTRODUCTION

Fouling in shell and tube heat exchangers is a prevalent issue that often leads to periodic shutdowns of industrial plants and underutilization of waste heat. This problem is exacerbated when utilizing low-temperature energy sources, like waste heat from industrial processes, as it can result in a decreased level of heat recovery. When this happens, supplementary energy sources, such as natural gas, must be used, which in turn increases the carbon footprint. Coatings that are typically applied inside these tubes tend to lose their effectiveness rapidly due to abrasion and wear, which strips away the protective layer. A viable solution to both mitigate fouling and facilitate easy cleaning, while also providing wear resistance, is the application of DLC-type (diamond-like carbon) coatings. There is documented evidence of DLC's benefits in reducing crystallization, whey-protein, and biofouling [1, 2, 3, 4]. However, the process industry faces challenges in adopting this technology, primarily due to the perceived high costs of coating and the limited size of existing coating facilities, which are generally designed for smaller components, such as tools for high-pressure pumps. Furthermore, there is an unexplored area of research in the production of industrial tubes with the dimensions and lengths that are necessary for constructing large heat exchangers.

Fig. 1. MICROPULS® Diamond Xtended system, RUBIG Group.

In 2021, Pillaca et al. [5] conducted an experiment that involved a specialized setup for applying an inner DLC coating to a single tube measuring 2000 mm in length and 100 mm in diameter. This experiment highlighted the need for

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further advancements to achieve smaller inner diameters—around 20 mm—which are more practical for shell and tube heat exchangers.

Fig. 2. Slit tube for procedure G – Gap coating.

Tab. 1. Procedure G – Gap coated tubes

No.	Step	Comment
G01	Cutting of standard tube	A standard tube of intended material and quality is cut to the final length (or intermediate length)
G02	Milling of longitudinal slit	A longitudinal slit in the range of 2 mm has been found sufficient for inner coating of a D_e25x2mm tube
G03	Coating of the tube inside and outside in a DLC-reactor	The possible scale-up of the reactor is 6 m and more. At present there are apparatus available with 2.3 m in length.
G04	Forming and welding of longitudinal slit	The heat input during welding is challenging to apply given form tolerances
G05	Milling of the ends	Cutting or milling operation is necessary before subsequent orbital welding
G06	Orbital welding	If the length is not sufficient, there is orbital welding of two or more pieces
G07	Straightening	In case straightness demands are not met after orbital welding
G08	Quality assurance	There are steps and tests to be done, which are requested by customers and authorities

The research team at the University of Applied Sciences Upper Austria in Wels (FH OOE) is actively working on the industrial application of DLC coatings for heat exchangers, utilizing PACVD (plasma-assisted chemical vapor deposition) technology from the RUBIG Group, Austria (Fig.1) [6]. The process involves heating the tubes to temperatures between 450 - 550°C and initiating plasma with pulsed DC power [7]. The experiments, as documented in [8] and [9], employed stainless steel tubes (1.4571/316Ti) with an outer diameter of 25 mm and a wall thickness of 2 mm. The goal for this research project is to produce pipes with a final length of 6000 mm, suitable for large-scale heat exchanger construction.

The research explored two distinct production methods. The first, procedure G, involves gap-coating for elongated tubes. This is achieved by applying an inner coating in a PACVD reactor through a narrow slit approximately 2 mm wide (Fig. 2). The result is a fine, uniform coating that creates engineered DLC-type surfaces, tailored to specific fluids and operational conditions [7, 9]. The application process is outlined in several steps, with the most significant challenge being step G04, which entails welding the longitudinal slit using laser technology. If the tubes do not meet the required straightness, step G07 is implemented, a topic that is elaborated upon in the chapter "Straightness of Tubes."

Tab. 2. Procedure C – Cavity coated tubes

No.	Step	Comment
C01	Cutting of standard tube	A standard tube of intended material and quality is cut to the maximum length for suitable coating
C02	Coating of the tube inside and outside in a DLC-reactor	The coating thickness and properties may vary in the cavity, which gives the maximum length applicable
C03	Orbital welding	Orbital welding of pieces to achieve required length
C04	Straightening	In case straightness demands are not met after orbital welding
C05	Quality assurance	There are steps and tests to be done, which are requested by customers and authorities

The second method, procedure C or cavity coating, is designed for shorter, individual tube segments. This process employs a specialized setup within the reactor to enhance the interaction with the plasma inside. In situations that demand specially engineered DLC-type surfaces, the maximum length for a satisfactory coating is shorter than what gap-coating achieves. For more information, please refer to the chapter titled 'Procedure C – Cavity Coating'. The advantage of the cavity coating process lies in its use of orbital welding to get lengths suitable for industrial applications, a technique that is already a well-established standard (see Tab. 2 step C03). This

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method was put to the test at Polysoude Austria's Admont facility, with the outcomes and insights discussed in the subsequent sections. While procedure C may be more immediately applicable to industrial needs, procedure G holds greater promise for harnessing the full spectrum of DLC and other potential coatings that can be applied in PACVD reactors by adjusting doping elements and other process variables.

PROCEDURE G – GAP COATING

Laser welding technologies were employed in the initial forming and welding tests. This method was chosen over Tungsten inert gas welding (TIG) because TIG's high heat input compromises the tube's form stability, even with optimal clamping. Laser welding, while not commonly used in shell and tube heat exchanger design, offers significant advantages: it eliminates the need for welding filler material and allows for very precise power management, which limits the heat-affected zone. Current tests are exploring the use of a clamping device that creates a zero-gap in the tube.

Comparatively, the orbital welding process (Step G06 in Tab. 1) presents more challenges than Step C03 (referenced in Tab. 2) of procedure C. This is due to the need for precise alignment of the longitudinal welds, making the weld preparation process more demanding.

PROCEDURE C – CAVITY COATING

Most tests using the C – cavity coating process were performed on samples with a length of 400 mm, and the inner coating exhibits a quiet uniform thickness over the entire length.

Test at FH OOE on the coating of cavities showed that producing a tube with RUBIG-type PACVD reactor (Fig. 1) has two effects, that are relevant in the context of fouling-mitigation.

1) Coating thickness variation: Thickness decreases with depth. Equation (1) gives an estimate of the inner layer thickness, wherein $h(x)$ is the interior coating thickness dependent on x, the distance from the opening. For smaller values x_k the full thickness h_0 becomes relevant. The thickness exhibits an exponential decline with the factor k for x greater x_k. Both factors x_k and k differ with the inner diameter D_i and the processing parameters, such as temperature and doping elements. For the case discussed in Fig. 3 there was an inner diameter of Di = 21 mm assumed. If the diameter would be double a decrease of the factor k by 90% can be expected, whereas x_k is quite constant. Thus, the minimum layer thickness specified at the tube's midpoint dictates the thickness at both the exterior and the openings. The implications for heat transfer are further detailed in the description of Fig. 3.

$$h(x) = h_0 \qquad x < x_k \qquad (1)$$

$$h(x) = h_0 \cdot e^{-k(x-x_k)} \qquad x \geq x_k$$

2) Doping elements effects: Utilizing doping elements like silicon (Si) results in a decrease of Si content in the inner layer at relatively short distances from the entrance. This phenomenon allows for the engineering of surfaces such as a-C:H:Si on the exterior, while the interior consistently exhibits a-C:H with no significant doping due to the depletion of precursor elements. Consequently, the exterior can be tailored to the specific medium and temperatures by adjusting the doping elements, offering a versatile "one-size-fits-all" solution for the interior. Literature has shown that these a-C:H layers are effective in mitigating fouling and provide sufficient wear resistance in numerous applications.

Eq. (1) is utilized to demonstrate the impact of overcoating on heat transfer, as the DLC layer acts as a barrier. Fig. 3 presents a model for coating a tube within a reactor. Initially, the layer maintains a thickness of h_0, which then decreases exponentially to $h_{l/2}$ at the midpoint $l/2$. However, the exterior thickness remains consistently at h_0 [9].

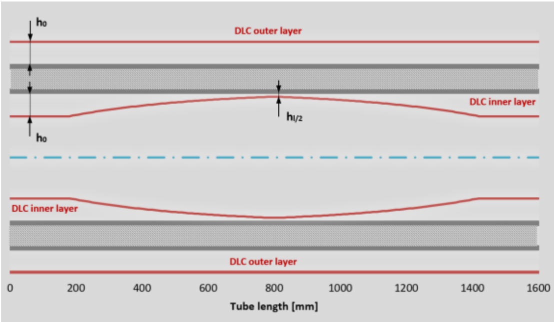

Fig. 3. Coating layer thickness (symbolically).

Assuming the values listed below, two cases were calculated, as there is a wide range given for the heat transfer rate of DLC (a-C:H – type) in [10]. In the case of $\lambda_{DLC,1}$ = 1 W/K m the additional average heat resistance was R_1 = 0.35·10^{-4} [m^2 K/W], in the other case $\lambda_{DLC,2}$ = 0.2 W/K m it came to R_2 = 1.75·10^{-4} [m^2 K/W], so the average heat resistance is R_{avr} = 1.05·10^{-4} [m^2 K/W].

Values:

h_0 = 20.3 µm (calculated layer thickness at the ends)

$h_{l/2}$ = 8 µm (given layer thickness inside, middle position)

k = 0.0015 mm^{-1}

l_k = 180 mm (length of constant thickness)

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l = 1600 mm (length of thought tube)
D_o = 25 mm (outer diameter)
s = 2 mm (wall thickness)
material: 1.4571/316Ti (stainless steel)
λ_{St} = 15 W/K m (heat transfer rate stainless steel)
λ_{DLC} = 0.2 to 1 W/K m (heat transfer rate DLC acc. [10])

To contextualize the impact of DLC coatings on heat transfer, let's consider the data from a study involving a CaSO4-H2O solution (2.5 g/l) on stainless steel, where the wall temperature was 75°C and the fluid temperature was 42°C, as presented in Fig. 4 [1]. Initially, DLC coatings tend to reduce heat transfer capacity. However, with an optimal combination of DLC type, fluid, and wall temperature, the induction period—during which fouling does not occur—can be significantly extended, resulting in less intense fouling. This also makes the tube easier to clean, thus reducing downtime. According to the experimental data, the induction period (t_{ind}) lasted 85 hours, but with a DLC coating, the break-even point—where the benefits of the coating outweigh the initial loss in heat transfer—occurs after 130 hours.

To minimize the initial resistance caused by the DLC coating, two strategies can be employed:

1) Selective coating: Applying the coating to only one side of the tube can be beneficial, especially if one side is known to remain clean, allowing the coating on the other side to be omitted.
2) Thickness adjustment: Reducing the coating thickness in the middle section of the tube, where abrasion is less of a concern, can enhance performance.

When shorter tubes are used, the initial coating thickness is reduced, but this necessitates more orbital welds, leading to economic rather than heat transfer inefficiencies. The uncoated area is minimal, estimated to be about 2% as indicated in Tab. 5.

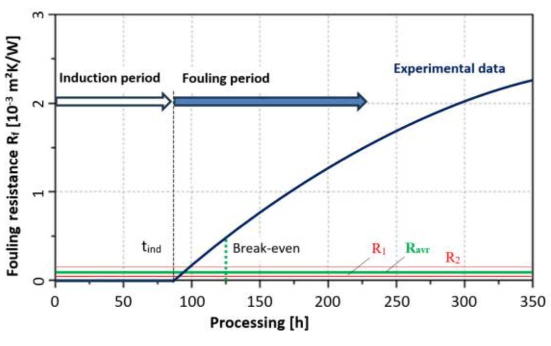

Fig. 4. Fouling curve for CaSO4 solution – experimental data acc. [1] and DLC heat transfer resistance calculation.

Orbital welding tests conducted at Polysoude, as depicted in Fig. 5, suggest that weld joints should remain uncoated [11]. While welding is possible on fully coated ends, a slight increase in carbon content by 0.02% was observed in the weld seam using the GDEOS method. This could be problematic in applications requiring high corrosion resistance, as noted in Tab. 3, line 02. Additionally, less favorable grain formations were observed in the micrograph.

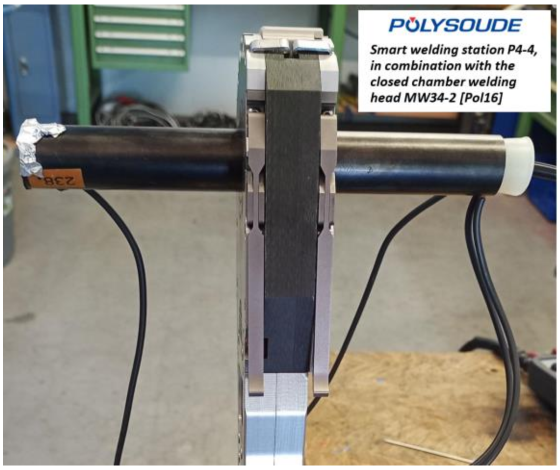

Fig. 5. Set-up for orbital welding.

For optimal seam quality, a design approach similar to that shown in Fig. 6 is recommended. This approach can be easily scaled up industrially; for example, a thin-walled cape used during the coating process can prevent the layer from being applied to the weld zone. Subsequent tests indicated that the maximum uncoated lengths measured after pickling were 8.2 mm and 6.4 mm, leading to further testing with external uncoated lengths (y_e) of 4 mm and internal uncoated lengths (y_i) of 3 mm [9].

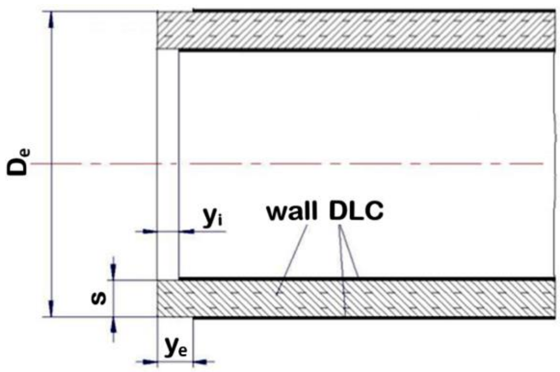

Fig. 6. Uncoated blanks for proper orbital welding.

Tab. 3 presents the results of experiments with various y_e and y_i values, aiming to identify the minimum coating shortfall (u) that still yields satisfactory welding results. The welds were assessed to be on par with those of uncoated tubes, as indicated in line 01.

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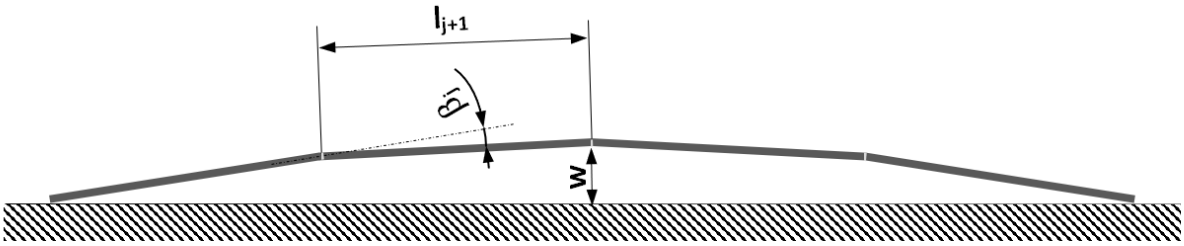

Fig. 7 Straightness model of orbital welded tubes.

Tab. 3. Coating shortfall u at weld seams (material 1.4571/316Ti)

No.	y_e [mm]	y_i [mm]	u_e [mm]	u_i [mm]	ΔC [%w/w]	R_m [MPa]	ε_f (l_0 = 25 mm acc. DIN-50125) [%]	Micrograph
01						559	22	satisfactory
02	0	0	8.2	6.4	0.02	589	22	unsatisfactory
03	3	2	7.1	5.4	0.008	534	17	unsatisfactory
04	4	3	8.5	5.9	0.004	535	20	satisfactory
05	5	4	9.9	7.9	0.006	560	29	satisfactory

Tab. 4. Straightness study of orbital welded tubes

No.	Set	j_{max}	$\bar{l}$	l_{tot}	w	$\bar{\beta}$	w^*/m	κ	κ/κ_{mean}	w_{mean}
			[mm]	[mm]	[mm]	[°]	[mm/m]	[1/mm]	[1]	[mm]
1	Trial 01	4	400	1600	4.77	0.34	1.86	$1.49\cdot10^{-5}$	7.5	0.6
2	Trial 02	4	400	1600	2.99	0.21	1.17	$9.34\cdot10^{-6}$	4.7	0.6
3	Avr-Trial	4	400	1600	3.88	0.28	1.52	$1.21\cdot10^{-5}$	6.1	0.6
4	Calc01	15	400	6000	54.3	0.28	1.51	$1.21\cdot10^{-5}$	6.0	9.0
5	Calc02	9	700	6300	34.0	0.28	0.86	$6.84\cdot10^{-6}$	3.4	9.9
6	Calc03	4	1600	6400	15.52	0.28	0.38	$3.03\cdot10^{-6}$	1.5	10.2
7	Strait01	4	400	1600	0.5	0.04	0.20	$1.56\cdot10^{-6}$	0.8	0.6
8	Strait02	4	400	1600	0.35	0.03	0.14	$1.09\cdot10^{-6}$	0.5	0.6
9	Avr-Strait	4	400	1600	0.425	0.03	0.17	$1.33\cdot10^{-6}$	0.7	0.6
10	Calc04	15	400	6000	6.0	0.03	0.17	$1.32\cdot10^{-6}$	0.7	9.0
11	Calc05	9	700	6300	3.7	0.03	0.09	$7.50\cdot10^{-7}$	0.4	9.9
12	Calc06	4	1600	6400	1.7	0.03	0.04	$3.32\cdot10^{-7}$	0.2	10.2
13	EN-10217 ASTM-ASME			6000	9	0.00	0.25	$2.00\cdot10^{-6}$	1.0	9.0
14	EN-10217 ASTM-ASME			1000	3	0.00	3.00	$2.40E\cdot10^{-5}$	12.0	0.3

Tab. 5. DLC-coverage

No.	j_{max}	$\bar{l}$ [mm]	l_{tot} [mm]	y_e [mm]	y_i [mm]	u_e [mm]	u_i [mm]	$A_{C,e}/A_e$ [%]	$A_{C,i}/A_i$ [%]
01	15	400	6000	4	3	8.5	5.9	98.0%	98.6%
02	9	700	6300	4	3	8.5	5.9	98.9%	99.3%
03	15	400	6000	5	4	9.9	7.9	97.7%	98.2%
04	9	700	6300	5	4	9.9	7.9	98.7%	99.0%

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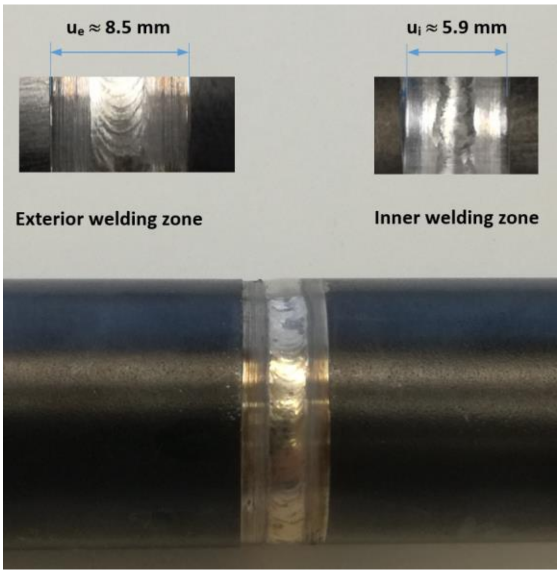

Fig. 8. Orbital welding test documentation with blank ends of y_e = 4 mm, y_i = 3 mm.

The three test sets, lines 03 to 05, showed no significant increase in carbon content compared to the base material, which has a maximum carbon content of 0.08% for 1.4571/316Ti. The GDEOS method's accuracy is estimated at 0.008%. The base carbon content outside the weld zone was found to be 0.013%, with all additional carbon measurements within the method's accuracy range, as shown in Tab. 3.

Tensile strength (R_m) measurement of the weld offered no significant outcome. More relevant is the discussion of ε_f (elongation at fracture), which was evaluated based on l_0 = 25 mm acc. DIN 50125 (Testing of metallic materials – Tensile test pieces). The 2 mm thick, non-proportional type samples were comparable to the standard value of a minimum of 40% for the given material. The values in lines 01, 04 and 05 can be seen as a basis for the comparison. Line 03 lies marginally below that standard value, so a beginning of significant more brittleness cannot be found here. It is notable that the additional carbon content in sample02 did not result in a deviation of ε_f. The micrograph of sample02 was unsatisfactory, and in sample03 deviations were found, whereas all other sets were rated as "good".

In summary, the blank ends with y_e of 4 mm and y_i of 3 mm, as seen in sample 04, are deemed sufficient. The measured coating shortfall, or uncoated weld area, is u_e of 8.5 mm and u_i of 5.9 mm, as illustrated in Fig. 8.

STRAIGHTNESS OF TUBES

Due to manufacturing characteristics with orbital welding and the effects of clamping before welding, there is deviation in the straightness of the tubes. The tests consisted of two 1.6 m tubes made of 4 pcs of 400 mm tubes coated with DLC and blank ends with y_e = 4 mm, y_i = 3 mm. A clamping device (Fig. 9) was used to facilitate a precise adjustment of the tubes. As the orbital welding head always performs the same procedure once programed, a basic finding revealed that the deviation appears roughly in a plane and consists of a more less constant offset in angle. The effect results from the fact that more energy is needed at the starting position than with the rest of the path around the tube. There are means to adjust the orbital welder to further minimize said offset, but this optimization procedure was not carried out for the tests presented here, as the focus was on the quality of the weld with respect to mechanical and metallurgical properties (Tab.3).


Fig.9. Clamping device for orbital welding

Fig. 7 depicts a model of orbital welded tubes with respect to straightness. In standards such as EN 10217 (Welded tubes for pressure purpose), the specification of straightness is denoted by a so-called deviation, w, over total length l. The standard specifies that the deviation in straightness of any tube length l shall not exceed 0.0015 l, and deviations in straightness over a one-meter length shall not exceed 3 mm. Of keen interest here is the fact that the deviation w is dependent on curvature κ, although there is no linear relationship between the length and deviation, rather the deviation is dependent on the square of length l. Using an arc as a model for tube straightness for small values of w compared to l (see Fig. 10), one can see that with linearization terms curvature κ can be found using Eq. (3).

$$w = \frac{l^2}{8r} = \frac{l^2 \kappa}{8} \quad (2)$$

$$\kappa = \frac{8w}{l^2} \quad (3)$$

When applying EN 10217 for 6 m tubes, there result a maximum of w = 9 mm, and using Eq. (3) the allowed curvature is $\kappa = 2.0 \cdot 10^{-6}$ 1/mm, which is the strictest requirement, as the value would be substantially lower at shorter lengths. Other standards such as ASTM-ASME are similar, whereby API-5L is slightly less demanding.

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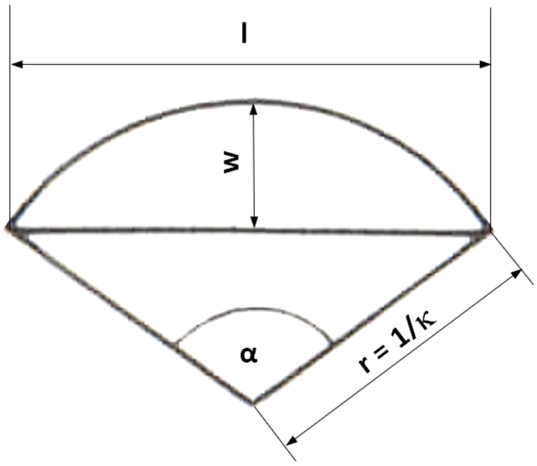

Fig.10. Arc model for tube straightness study

Results in straightness from the tests are evaluated acc. Fig. 7. If one sets j_{max} the total number of tubes and $\bar{\beta}$ the average of small angle deviations β_j and $\bar{l}$ the average of tube lengths l_j, then there are two cases for the estimate of deflection w:

$$j_{max} = 2n \ (n \in \mathbb{N}) \qquad w = \frac{1}{8}\bar{l}\bar{\beta}\, j_{max}^2 \qquad (4)$$

$$j_{max} = 2n + 1 \ (n \in \mathbb{N}) \quad w = \frac{1}{8}\bar{l}\bar{\beta}\, (j_{max}^2 - 1) \qquad (5)$$

using linearization of type $\sin(\beta_j) \approx \beta_j$.

With eq. (4) and (5) it is possible to calculate $\bar{\beta}$ from a measured value w. Trials yielded the values in Tab. 4, lines 01 and 02. 4 pcs á 400 mm ($\bar{l}$) were welded together to achieve a total length l_{tot} of 1600 mm. Eq. (4) is used to determine the average value of angle deviation, $\bar{\beta}$, and Eq. (3) the curvature κ. Line 03 in the table gives the average of $\bar{\beta}$ and calculates the resulting values for reference. With $\bar{\beta}$, Calc01 to Calc03 are performed, simulating the results, in case some 6m long tubes are produced with given parameters, whereby Calc01 dealt with 400 mm pieces, Calc02 with 700 mm pieces and Calc03 with 1600 mm pieces. Current trials at RUBIG industrial reactors (Fig. 1) have revealed that the cavity-coating of about 700 mm tubes at D_e 25 mm can be done with the set up describe herein. The straightness to be expected is w = 34 mm while the value w_{mean} = 9.9 mm represents the limit given by EN-10217 (line 13). For such cases, production step C04 acc. Tab. 2 should be implemented. In the trial discussed here, this was performed by hand in the workshop of FH OOE by a skilled worker, whereas standard straighteners would be used at the industrial scale. The results can be found in lines 07 and 08 with the average w = 0.425 mm (line 09). Calc04 shows the calculation for ranges of up to 6000 mm, and the resulting w = 6.0 mm fully achieves the target value 9 mm. With 700 mm pieces this value is reduced further to 3.7 mm (Calc05).

Fig.11. 1.600 mm DLC-coated tube

RESIDUAL FOULING

In the context of the C-route's advancement, a pivotal question arises: How effective is the DLC coating at protecting tubes against fouling, as depicted in Fig. 11. Reflecting on Fig. 6 and the insights from Tab. 3, line 04, where the setup with external diameter (y_e = 4) mm and internal diameter (y_i = 3) mm was deemed satisfactory, further calculations were undertaken. Tab. 5 delineates a comparison between using 400 mm and 700 mm segments, specifically for the aforementioned dimensions, as per Fig. 6. The external protection is robust, ranging between 98% to 99%, with marginally higher values internally. A larger blank area, as discussed in lines 03 and 04, results in a negligible decrease of 0.3% externally and 0.4% internally. The disparity in protection when comparing 400 mm to 700 mm segments is minimal, at 0.9% and 0.7%, respectively.

CONCLUSION AND OUTLOOK

A standardized production pathway has been established for 6-meter DLC-coated heat exchanger tubes, featuring a diameter of 25 mm and a thickness of 2 mm, crafted from 1.4571/316Ti stainless steel. The DLC-protected area is approximately 98% to 99%, contingent on the tube lengths and weld preparations, as indicated in Tab. 5, lines 01 and 02. This translates to a significant enhancement in fouling protection, with a 98% to 99% improvement when compared with non-coated products.

An economic assessment is slated for a subsequent phase of the project. Within this scope, two principal cost factors pertinent to the C-route cavity coating, as listed in Tab. 2, will undergo a thorough evaluation. Step C02 is anticipated to be more cost-effective with shorter tubes, such as the 400 mm ones illustrated in Fig. 3. Although the 700 mm tubes necessitate a lengthier processing time to ensure adequate exterior thickness for the requisite interior thickness, the reactor's filling capacity, as shown in Fig. 1, should yield comparable outcomes for both tube lengths. Equation (1) intimates a factor of roughly 25%, but the actual impact can only be ascertained through experimental runs. This would also result in greater initial heat resistance of the coating system (Fig. 3).

Reducing the number of orbital welds, as per step C04, is decidedly beneficial. Tab. 4 indicates

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that 15 orbital welds are necessary for 400 mm tubes, whereas only 9 are needed for 700 mm tubes, equating to a 40% reduction and consequently, a lesser deviation in straightness. The costs associated with orbital welding, assuming an optimal setup, should remain manageable for both tube lengths.

A preliminary endorsement can be extended towards the 400 mm solution, primarily due to the diminished coating expenses.

Further empirical research within an operational setting would greatly contribute to validating the concept and uncovering additional avenues for enhancement. The remaining challenge is to orchestrate an initial application, potentially with a modest batch of ten tubes for experimental purposes, during which the actual economic viability can be assessed. Testing under authentic conditions presupposes four criteria:

1) An operation grappling with severe fouling issues or aspiring for a marked improvement.
2) Recognition of DLC as a potential solution for the fouling dilemma.
3) The operation's proprietor's readiness to finance tests involving DLC-coated tubes.
4) Endorsement from the relevant authorities for the approach utilizing orbital welded tubes.

REMARK

Should the fouling issue be confined to the exterior, all aforementioned factors retain their relevance. At RUBIG's Marchtrenk facility, the application of various DLC-type coatings to 1600 mm segments is feasible. The assembly of merely four segments culminates in a ready-to-deploy, easy to clean heat exchanger tube, safeguarded against fouling, suitable for a broad spectrum of high-temperature and high-pressure scenarios.

Acknowledgement

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NOMENCLATURE

A	Area, mm²
D	Diameter, mm
h	Coating thickness, µm
j	counter
k	Factor of decline, mm^{-1}
l	length, e.g. of tube, mm
n	Natural number
R	Heat resistance, m^2 K/W
R_m	Tensile strength, MPa
r	Radius, mm
s	Thickness of wall, e.g. of tube, mm
t	Time, h
u	Shortfall of coating (uncoated length), mm
w	Straightness deviation, mm
x	Length, coordinate, mm
y	Length, e.g. of blank, mm
ΔC	Additional carbon content, %w/w
β	Angel of deviation, °
ε	Strain, %
κ	Curvature, 1/mm
λ	Heat transfer rate, W/K m

Subscript

0	base
avr	average
C	coating
DLC	for DLC-coating
e	exterior
f	fouling
i	inner
j	counter
k	critical point
max	maximum
mean	mean value
St	steel
tot	total

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