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Materials Selection for Superheater Tubes in Municipal Solid Waste Incineration Plants

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Corrosion reduces the lifetime of municipal solid waste incineration (MSWI) superheater tubes more than any other cause. It can be minimized by the careful selection of those materials that are most resistant to corrosion under operating conditions. Since thousands of different materials are already known and many more are developed every year, here the selection methodology developed by Prof. Ashby of the University of Cambridge was used to evaluate the performance of different materials to be used as MSWI superheater tubes. The proposed materials can operate at steam pressures and temperatures over 40 bars and 400 °C, respectively. Two case studies are presented: one makes a balanced selection between mechanical properties and cost per thermal unit; and the other focuses on increasing tube lifetime. The balanced selection showed that AISI 410 martensitic stainless steel (wrought, hard tempered) is the best candidate with a good combination of corrosion resistance, a relatively low price (0.83-0.92 €/kg) and a good thermal conductivity (23-27 W/m K). Meanwhile, Nitronic 50/XM-19 stainless steel is the most promising candidate for long-term selection, as it presents high corrosion resistance with a relatively low price (4.86-5.14 €/kg) compared to Ni-alloys.

Keywords corrosion, heat exchanger tube, material selection, municipal solid waste incineration plant, Ni-alloys, stainless steel

1. Introduction

In the combustion boilers of municipal solid waste incineration (MSWI) also well-known as waste-to-energy (WtE) plants, corrosion problems occur. Numerous incidents of corrosion and erosion-corrosion of waterwall tubes, superheater tubes, and other pressure parts have been widely reported (Ref 1). In general terms, the main causes that lead to MSWI boiler tubes reaching the end of their useful life are well known. The flue gas environment is very aggressive, due to gas components, such as HCl, SO_2, CO, Cl_2, alkali metals, and heavy metals (Zn, Sn, …), which form chlorides with high vapor pressures (Ref 2). The problems are often aggravated by variations in the mixed fuel including periods of a high chlorine load. Chlorine in MSW mainly originates in polyvinyl chloride (PVC) and sodium chloride (NaCl) contained in the household rubbish that feeds the combustion chamber. The generated gases are deposited on tube walls by condensation or sublimation (Ref 3). Moreover, soft and sticky particles can be adhered to the heat transfer surfaces. These deposits contain salts such as chlorides, sulfates, oxides, and unburned particles, and thus result in low oxygen partial pressures near the metal surface. In addition, the melting and fluxing of low-melting-point compounds can accelerate corrosion, due to the formation of volatile metal chlorides, thus resulting in the formation of internal voids.

A lot of information on corrosion mechanisms and the effects of temperature and the formation of deposits can be found in the literature (Ref 4, 5). It is generally accepted that the high level of chlorides in waste is the main cause of corrosion. High-temperature corrosion in WtE plants is caused by chlorine either in the form of HCl, Cl_2, or combined with Na, K, Zn, Pb, Sn, and other elements (Ref 6). In particular, HCl gas, with a highly reducing atmosphere, and molten chlorides within the deposit are considered major factors. Sulfur compounds can be corrosive at high temperatures, thus their presence can make corrosion caused by chlorine a less important factor (Ref 7, 8). The factors that most affect the corrosion of the boiler are the metal temperature, temperature difference between gas and metal, flue gas composition, formation of deposits, and reducing conditions; as well as the SO_2/HCl ratio (Ref 9, 10).

The boiler zones most sensitive to corrosion are the superheater tubes, as a result of the high temperatures and high pressures inside. Commonly, WtE plants are operated at steam pressures of 40 bars and a steam temperature of 400 °C. However, further increases in boiler steam pressure and final temperature are desirable to increase the energy cycle efficiency; and some modern WtE plants can operate at higher steam parameters. For instance, new concepts allow the steam parameters to be increased to 440 °C and 130 bars (Ref 11). High-temperature corrosion is a thermally activated process; increased temperatures will therefore increase the potential for accelerated corrosion (Ref 12). Increased steam pressure will increase the maximum temperature within the superheater tubes, which will lead to an increase in the corrosion rate, even if the deposition of molten chlorides can be prevented by modifications to the corrosive environment, such as increasing turbulence (Ref 13). In such circumstances, better knowledge

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of the location in the boiler of the predominant corrosive environment could greatly assist effective alloy selection and use.

When WtE plants are operated at standard steam conditions (400 °C and 40 bars), 15Mo3 steel, which is a low-alloy steel with 0.3% Mo, is currently used. However, low-alloy steels cannot resist corrosion at steam parameters higher than standard, even if chlorine is present only at low concentrations (Ref 14, 15). Materials with adequate corrosion resistance to reducing combustion atmospheres that contain chlorine are highly alloyed, and thus expensive. The use of coatings is often justified because of difficulties associated with mechanical properties, workability, and the high price of high-alloy materials. Several methods for tube coating have been reported: co-extrusion (Ref 16), weld overlaying (Ref 17), diffusion coating (Ref 18), thermal spraying (Ref 19), and laser cladding (Ref 20).

Ni-based alloys are considered the most heat-resistant alloys. Corrosion via the formation of nickel chloride is more difficult than it is via Fe chlorides, and nickel chloride is less volatile than Fe chlorides are. The resistance of ferrous alloys increases as the Fe content decreases. In contrast, corrosion by HCl decreases with an increase in Cr and Mo contents. Several electrochemical studies performed using melted chloride salts have shown that additions of Mo can reduce the corrosion rate (Ref 21). In addition, the studies have shown that Ni additions are beneficial due to the formation of NiO, and mixed Ni and Fe chromites, which are less soluble in melted chloride salts than chromium oxides are (Ref 22, 23). Ishitsuka and Nose (Ref 24) showed that the addition of Mo_2O_3 to a synthetic waste incineration deposit has the effect of partially reducing the corrosion rate of AISI304 stainless steel by decreasing the solubility of Cr_2O_3. Additions of W or V are expected to present the same effect. Therefore, alloying additions of Ni, Cr, Mo, and W reduce the corrosion rate synergistically (Ref 21, 25).

Corrosion problems can be minimized by careful materials selection that are resistant to corrosion under operating conditions. Unfortunately, the choice of a boiler material is frequently the result of several compromises between, for example, corrosion resistance and mechanical strength or thermal conductivity. Moreover, the final selection may come down to a compromise between technical and economic factors. In WtE boilers, mechanical and thermal requirements, such as a high yield strength and thermal conductivity, are hard to accommodate while optimizing corrosion resistance and cost. Commonly, the most corrosion resistant materials are the most expensive.

Browsing or searching in handbooks and databases is useful for materials selection, especially when the selection process depends on only one or two properties. It seems easy to establish the proper relationships between key material properties. However, the difficulty lies in establishing the proper relationships/weightings/etc. between key factors and in finding all of the necessary data across classes of materials so that comparisons can be made. The aim of this work is to fill this gap for WtE plant superheater tubes. The Ashby approach was chosen as the method to achieve this goal. Various studies help address other issues of materials selection (Ref 26-30). This selection strategy was developed by Prof. Ashby and co-workers at the University of Cambridge, UK (Ref 31). It is based on the use of Granta's CES Selector software 2012 to construct charts of the properties of materials (Ref 32). In this work, suitable materials for use in WtE plant superheater tubes were determined for two case studies: long-term and balanced selections. First, the basis of the proposed approach with a short overview of methods for selecting materials, including the selection criteria and the objective function, is presented. Then, the results of the preliminary selection obtained via Granta's CES Selector software 2012 are discussed. From these data, the candidate alloys, which should fulfill the different constraints for the typical WtE plant superheater tubes, are presented for the two cases studied. Finally, the possible material candidates to be used for the superheater tubes are discussed, thus obtaining a ranking of the best candidates for each case.

2. Methodology for Materials Selection

In the context of superheater tubes design, the main goal of materials selection is to minimize cost maintaining the performance, as measured by key factors such as corrosion resistance. The materials selection is typically performed via intuitive and non-systematic approaches, which are based on the experience and inspiration of the engineers and researchers in a determined application. They often lead to a non-robust and subjective materials selection, especially when the studied system is complex and not well known. A systematic approach does not only lead to the selection of better quality materials than an intuitive one, but also more robust solutions are obtained under a wide variety of situations. In addition, the problems and decisions are quantitatively well-specified, the inputs are precisely defined and formulated, and it requires no more time than intuitive methods. In order to avoid the drawbacks of intuitive methods, systematic ones must be applied. Selection of the best material for a given application begins by studying the properties and the costs of candidate materials using materials databases; but their use for applications requiring multiple criteria, is complex.

In the present work, we used the CES Selector software, which is a practical and useful database of materials and processes (Ref 32, 33). The starting point is a set of technical requirements for a component or subsystem. These are transformed into a set of limits or target values for the material properties or property combinations ("material indices"). It is then possible, given a comprehensive database of appropriate materials and their properties, to screen materials against these criteria, rank those that pass according to the target value of one or more indices, and finally draw in other associated documentation to make an optimally informed decision. The reasoning is made transparent by displaying the steps and the materials that pass and fail the screening steps in material property charts that present materials on axes of their properties or of the material indices. In other words, the problem statement firstly clarifies the main component of the function that defines the field and working environment. For this purpose, the model from which the attribute limits emerge is proposed, thus identifying the function constraints, objectives, and free variables, such as minimizing material cost, maximizing performance, and other objectives, as commented on below. Finally, the full menu is reduced by screening, using the objective function, to obtain at a relatively short list of viable candidates. For the present case study, the constraints to take into account are as follows:

(i) Yield strength: the superheater tubes should be designed to perform their function without yielding to the internal pressure.

(ii) Thermal conductivity: heat has to flow through the material easily.
(iii) Corrosion resistance: the material should perform well in strongly corrosive environments.
(iv) Maximize service temperature: this is the highest temperature at which the material can be used continuously without oxidation, chemical change, or excessive distortion becoming a problem.
(v) Cost: it is important to choose the least expensive of the candidate materials.
(vi) Easy manufacturing: the material should be produce using the most common methods such as forging, casting, and/or welding.
(vii) Availability: the material should be available at the industrial scale.

Transforming these constraints into a mechanical design problem for a heat exchanger tube with a given tube radius operating at fixed pressure and temperature, by minimizing the material cost, C_m, and maintaining good mechanical and thermal properties, the selection process yields the following equation (Ref 32):

$$M = \frac{\sigma_y^2 \lambda}{C_m \rho}, \tag{Eq 1}$$

where M is the material index to be maximized; σ_y yield strength (MPa); λ, the thermal conductivity (W/m K); C_m, the material price (€/kg); and ρ, the material density (kg/m^3). In other words, this index maximizes the heat flow per unit area while maximizing the strength and minimizing the cost of the tube. In order to obtain this index, pressure, and thermal difference, radius and wall thickness have been considered as constant. Materials with the highest value of M are the best choice, provided that they also meet the other constraints stated above as selection criteria. Considering M as a constant, taking logs in the materials index equation and rearranging, we get:

$$\log \frac{\sigma_y^2}{\rho} = \log \frac{C_m}{\lambda} + \log M. \tag{Eq 2}$$

This is the equation corresponding to a straight line of slope 1 on a plot of log (σ_y^2/ρ) against log (C_m/λ).

3. Results and Discussion

3.1 Preliminary Materials Selection

Materials were preliminarily selected with the help of the CES Selector software. Figure 1 shows, on the x-axis, the cost per thermal unit, C_m/λ, and on the y-axis, the square strength per density unit, σ_y^2/ρ, for different ferrous, nickel, and refractory alloys. These alloy families seem to be good candidates for superheater tube applications, as they present a good relationship between corrosion resistance in aggressive environments (in the presence of chloride and sulfide species, for example), mechanical resistance, weldability, cost, and availability on the market in tubular shape. Only those alloys with a maximum service temperature over 400 °C, which is the standard service temperature in WtE plant superheaters, are plotted in the figure. A grid of lines corresponding to M values from 1 to 10,000 is also shown.

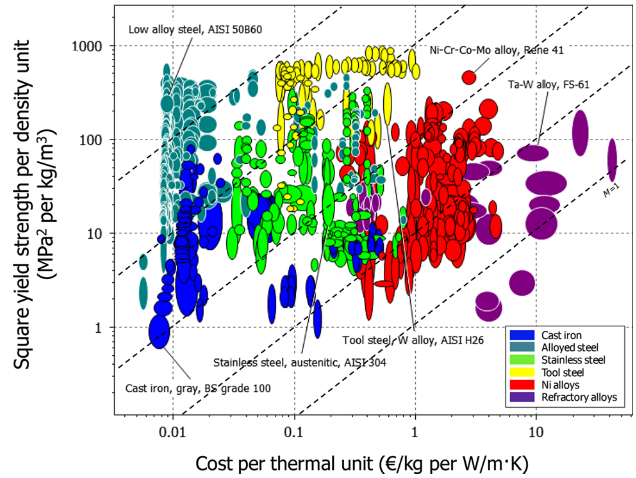

Fig. 1 Specific strength vs. cost per thermal unit for different ferrous, nickel, and refractory alloys, obtained with CES Selector

The best relation between yield strength squared per unit density and cost per thermal unit will be in the top left of the plot, which is the maximum value for M. All materials that lie on a line of constant M perform equally well in terms of strength squared per density and cost per thermal unit, while also performing well in strongly corrosive environments. Those materials above the line perform better and those below less well. Cast irons (in blue), alloyed steels (in dark green), tool steels (in yellow), and stainless steels (in clear green) exhibit the highest values of M; that is, the best relationship between yield strength squared and cost per thermal unit or the minimum cost per unit of heat flow. Among alloyed steels, those with a low-alloy content present high M values, such as those commonly used for heat-exchangers operating under standard steam conditions: 15Mo3 (DIN 17155) and St 35.8 (DIN 17175).

One of the constraints settled in the selection criteria is a minimum yield strength that allows an internal pressure of at least 40 bars, which is the typical steam pressure in WtE plants operating at 400 °C steam temperature. It can be estimated by the following equation (33):

$$\sigma = \frac{pR}{t}, \tag{Eq 3}$$

where σ is the minimum yield strength (MPa) of the tube to avoid a failure, due to the internal pressure, p (MPa); and R, outer radius (m) and t, the wall thickness (m) of the tube. If a tube with a diameter (2R) and wall thickness ratio of 5 is considered, which is typical for WtE plant superheater tubes, a yield strength of at least 20 MPa is necessary. However, the yield strength determined at room temperature progressively decreases with increasing service temperature. In addition, wall thickness also reduces with increasing operating time, due to the evolution of corrosion. Corrosion can be also heterogeneously distributed, thus being located at specific zones due to overheating phenomenon; this is manifested by the presence of significant deposits that lead to a considerable reduction in wall thickness and excessive fire-side heat input (Ref 15). Taking into account that the yield strength range of 320-400 MPa for the 15Mo3 steel typically used in WtE plant superheaters (Ref 15, 32), the minimum yield strength should be at least 400 MPa. Therefore, when applying this constraint to the previous selection, some materials are excluded from the plot.

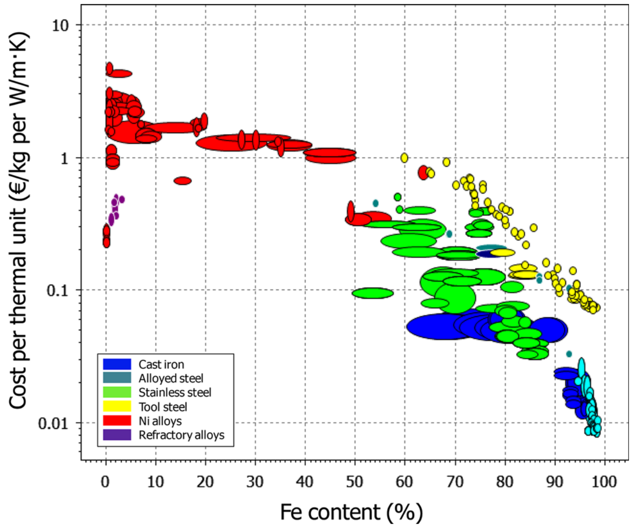

Fig. 2 Cost per thermal unit as a function of Fe content for different ferrous and non-ferrous alloys

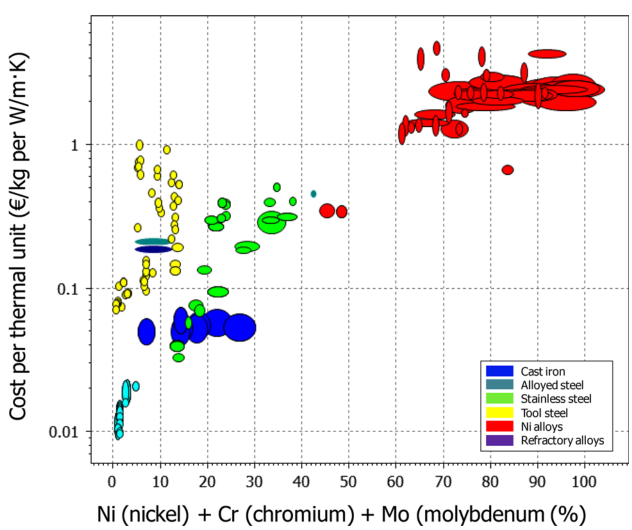

Fig. 3 Cost per thermal unit as a function of (Ni + Cr + Mo) content for different ferrous and non-ferrous alloys containing any amount of the three elements

In contrast, the cost per thermal unit is related to the composition of the material and as observed in Fig. 2, it decreases with increasing Fe content; however, it also increases with increasing content of alloying elements such as Ni, Cr, and Mo (Fig. 3). Cast irons are considered brittle, with a relatively low thermal and mechanical shock resistance, and so in accordance with these criteria, cast irons should not be selected for superheater tubes.

Other design constraints on the selected materials are the corrosion resistance and the workability. Most metal alloys present a high workability (Ref 34); so this property will only be studied for the materials finally selected, as it does not constitute a significant constraint in the selection process. In contrast, corrosion resistance is not easily quantified, and therefore, it is difficult to include in the materials selection. The properties of materials depend strongly on their composition, and in the case of the corrosion resistance of alloys, it can be modulated by varying the alloy composition. Some experimental studies that establish relationships between alloy composition and corrosion resistance by pitting can be found in the literature (Ref 35-40). A parameter that is an estimate of pitting resistance is the pitting resistance equivalent number (PREN). There are several PREN equations for each alloy family (Table 1). Some of the most common expressions for some stainless, duplex, and superaustenitic steels have been reported (Ref 35-37). Other equations show a common formula used to compare the pitting resistance in both stainless steels and nickel-based alloys (Ref 37, 38). According to those equations, the pitting resistance can be increased respect to the value the same content of Cr would yield, between 1.5- and 30-fold, depending on the element added. It is important to comment that the N addition is limited in these alloys, and the N solubility can be increased by the addition of Mn. In other work, the PRENs are only specified for Ni-alloys depending on the experimental conditions (Ref 39, 40). As a general tendency, it can be considered that an increase in Ni, Cr, and Mo content leads to an increase of the corrosion resistance for ferrous alloys. The oxidation products of these elements form protective layers, which restrict the oxidation process at the metal surface. Nevertheless, ferritic chromium steels containing high percentages of an alloying element become brittle in the range 300-600 °C, whereas this effect is lower for austenitic steels and not significant for steels with an Ni content greater than 30%. However, as can be seen in Fig. 3, the cost per thermal unit also increases.

Table 1 Factors of pitting resistance equivalent number (PREN) equations for different alloy families

	Factors of PREN equations for each element							
Alloy group	A_{Cr}	B_{Mo}	C_{Nb}	D_W	E_N	F_{Cu}	G_{Ni}	**References**
Stainless, duplex, and superaustenitic steels	1.0	3.3	…	16	…	…	…	[35, 36]
	1.0	1.5	1.0	30	…	…	…	[36, 37]
Stainless steels and Ni-based alloys	1.0	1.5	1.5	30	1.5	…	…	[37, 38]
	1.0	1.5	1.5	…	…	0.5	…	[39]
Ni-based alloys	1.0	2.0	1.0	…	…	…	…	[40](a)
	2.0	2.0	2.0	…	…	…	1.0	[40](b)

PREN = A_{Cr}·(%Cr) + B_{Mo}·(%Mo) + C_{Nb}·(%Nb) + D_W·(%W) + E_N·(%N) + F_{Cu}·(%Cu) + G_{Ni}·(%Ni). For Ni-alloys exposed at (a) 550 °C, and (b) 650 °C for 336 h in N_2-10%O_2-CO_2-20%H_2O-1500 ppm HCl-300 ppm SO_2

Even though numerical data related to PRENs for all ferrous and non-ferrous alloys cannot be included in the CES Selector software, the qualitative durability of the alloys in strong acid environments may be represented as shown in Fig. 4. All the alloys plotted in the figure have a yield strength higher than 400 MPa, a maximum service temperature over 400 °C, and an acceptable or excellent durability in strong acid media. From these criteria, those alloys with the lowest cost per thermal unit are austenitic, martensitic, ferritic, and duplex stainless steels. The best alternatives to stainless steels or ferrous alloys are the Ni-based alloys, although their cost per thermal unit is from 10 to 100 times higher. Table 2 summarizes some properties of the main ferrous and non-ferrous alloy families. As can be deduced from the data in the table, materials presenting the highest ratio between strength squared per density unit and cost per thermal unit (that is the highest M value) are not those with the best durability in strong acidic media. Thus, two case studies can be now formulated: a balanced selection to maximize the material index with a moderate durability in strong acid media, which translates to a shorter lifetime; and a long-term selection, where the corrosion resistance (or a longer lifetime) is preferred over a lower cost of the tubes.

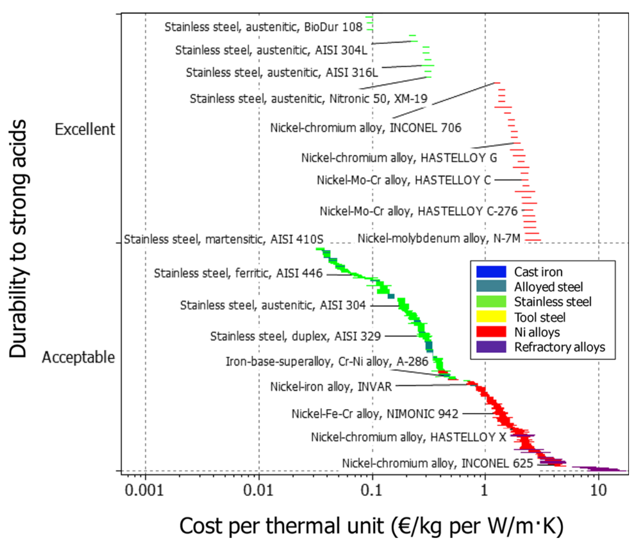

Fig. 4 Relationship between the corrosion resistance in strong acid environment and the cost per thermal unit for different ferrous and non-ferrous alloy families

3.2 Balanced Selection Case Study

To select a material with a balanced relation between cost and performance, the following limits have been applied as constraints that must be strictly satisfied:

(i) Yield strength ≥ 400 MPa.
(ii) Maximum service temperature ≥ 400 °C.
(iii) Durability in strong acid media: acceptable or excellent.

Figure 5 shows those materials that fulfill the requirements, with a cost per thermal unit lower than 1. Table 3 summarizes the properties of the elements plotted in Fig. 5 with the highest value for the material index. In this table, the materials are ranked according to their materials' indices using Eq 1. Martensitic and ferritic stainless steels are the best candidates, as they achieve a good compromise between mechanical properties and their cost per thermal unit, with good behavior in strong acid media. The main advantages of these steels are their high mechanical and corrosion resistance compared to the 15Mo3 steel (220-275 MPa, 37-49 W/m K) and St 35.8 steels (215-235 MPa, 35-50 W/m K) typically used (Ref 41). So, their yield strengths are relatively high, which is an important parameter when the material has to work at high pressures, and they present a thermal conductivity between 15 and 31 W/m K,

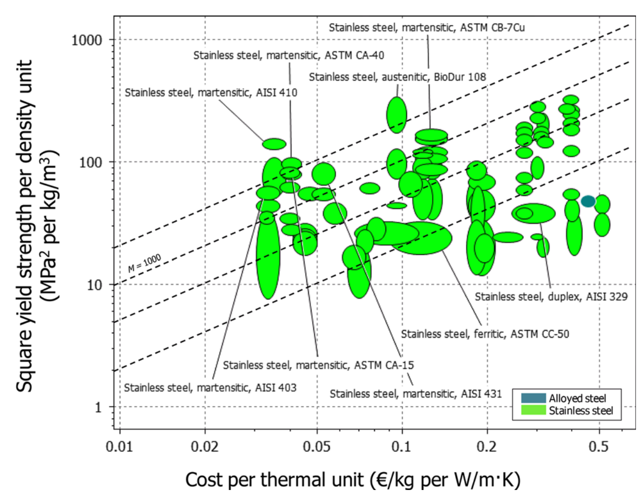

Fig. 5 Specific strength vs. cost per thermal unit for different alloys, obtained with CES Selector, with the balanced selection criteria

Table 2 Mechanical and thermal properties, corrosion resistance, and cost for different Fe- and Ni-alloys ranked by material index

Alloy group	Square yield strength per density unit, MPa^2 per kg/m^3	Cost, €/kg	Thermal conductivity, W/m K	Cost per thermal unit, €/kg per W/m kg	Material index	Durability to strong acids
Low-alloy steels	1-500	0.3-1.1	35-60	0.008-0.3	800-32,000	Unacceptable
Intermediate alloy steels	200-350	0.9-5	20-30	0.05-0.2	1600-8900	Unacceptable
Refractory alloys	1-210	32-1610	30-142	0.3-46	1-7800	Acceptable or excellent
Tool steels	15-1000	3-20	20-50	0.06-1	200-7300	Unacceptable
Cast irons	0.5-100	0.4-1.5	18-40	0.005-0.02	200-5600	Unacceptable
Martensitic stainless steels	5-350	1-6	15-30	0.1-0.6	140-4100	Acceptable
Austenitic stainless steels	10-350	1-9	15-20	0.1-1	60-2600	Acceptable or excellent
Ferritic stainless steels	5-35	2-3	15-30	0.05-1	200-500	Acceptable
Ni-based alloys	1-600	10-55	8-20	0.2-6	4-300	Acceptable or excellent
Duplex stainless steels	20-55	4-9	15-20	0.2-0.6	60-130	Acceptable

Table 3 Mechanical and thermal properties, corrosion resistance, cost, and material index for materials that best fulfill the balanced selection criteria

Alloy name	Yield strength, MPa	Cost, €/kg	Thermal conductivity, W/m K	Material index	Max. service temperature, °C	Durability to strong acids
AISI 410 martensitic stainless steel, wrought, hard temper	1000-1100	0.83-0.92	23-27	4050	700-800	Acceptable
BioDur 108 austenitic stainless steel, wrought, 30-40% cold worked	1160-1620	1.45-1.60	15-17	2580	750-790	Excellent
ASTM CA-40 martensitic stainless steel, cast, tempered at 595 °C	815-910	0.94-1.03	23-26	2420	535-585	Acceptable
AISI 410 martensitic stainless steel, wrought, intermediate temper	634-917	0.83-0.92	23-27	2140	700-800	Acceptable
ASTM CA-15 martensitic stainless steel, cast, tempered at 595 °C	755-835	0.92-1.02	23-26	2090	535-585	Acceptable
ASTM CA-40 martensitic stainless steel, cast, tempered at 650 °C	740-820	0.94-1.03	23-26	1980	590-640	Acceptable
AISI 403 martensitic stainless steel, wrought, hard temper	550-620	0.79-0.87	23-27	1330	700-750	Acceptable
ASTM CA-15 martensitic stainless steel, cast, tempered at 650 °C	655-725	0.92-1.02	23-26	1570	590-640	Acceptable
AISI 431 stainless steel, martensitic, wrought, tempered at 593 °C	715-875	0.95-1.03	23-27	1530	530-580	Acceptable
AISI 403 stainless steel martensitic, wrought, intermediate temper	550-620	0.79-0.87	23-27	1330	550-620	Acceptable

Table 4 Mechanical and thermal properties, corrosion resistance, cost and material index for materials that best fulfill the long-term selection criteria

Alloy name	Yield strength (MPa)	Cost (€/kg)	Thermal conductivity (W/m K)	Material index	Max. service temperature (°C)	Durability to strong acids
BioDur 108 austenitic stainless steel, wrought, 30-40% cold worked	1160-1620	1.45-1.60	15-17	2580	750-790	Excellent
BioDur 108 austenitic stainless steel, wrought, 10-20% cold worked	752-986	1.45-1.60	15-17	1020	750-790	Excellent
Nitronic 50, XM-19 austenitic stainless steel, wrought, cold drawn, wire (nitrogen strengthened)	1140-1400	4.86-5.14	15- 16	648	750-790	Excellent
BioDur 108 austenitic stainless steel, wrought, annealed	580-592	1.45-1.60	15-17	472	750-790	Excellent
ASTM F1586 austenitic stainless steel, wrought, medium hard, nitrogen strengthened	760-934	4.01-4.41	14	300	750-790	Excellent
INCONEL 706 nickel-chromium alloy, wrought, solution treated	896-1000	14.9-16.3	12-13	87.4	632-705	Excellent
ASTM F1586 austenitic stainless steel, wrought, annealed, nitrogen strengthened	432-452	4.01-4.41	14	82.5	750-790	Excellent
INCONEL 718 nickel-chromium alloy, wrought, solution treated, and aged	1000-1100	19.4-21.3	12-13	80	632-705	Excellent
Nitronic 50, XM-19 austenitic stainless steel, wrought, annealed (nitrogen strengthened)	363-434	4.68-5.14	15-16	64.2	750-790	Excellent
INCONEL 718 nickel-chromium alloy, wrought, solution treated	724-800	19.4-21.3	12-13	41.9	632-705	Excellent

which ensures a good exchange of heat at a low cost. Among these materials, AISI 410 martensitic stainless steel (wrought, hard tempered) performs the best from among all the candidates. This is a basic martensitic stainless steel that retains its mechanical properties after heat treatment and has a good corrosion resistance (Ref 42). The main applications of this steel are steam and gas turbine blades and buckets. The next best material is BioDur 108 austenitic stainless steel (wrought, 30-40% cold worked), which is a nickel-free alloy designed for medical applications. BioDur 108 exhibits both significantly higher corrosion resistance at room temperature and significantly higher strength than any of the common nickel-containing stainless alloys, in both the annealed and cold worked conditions, which is strongly related to levels of chromium, molybdenum, and nitrogen (Ref 43). However, it presents a low thermal conductivity and its corrosion resistance

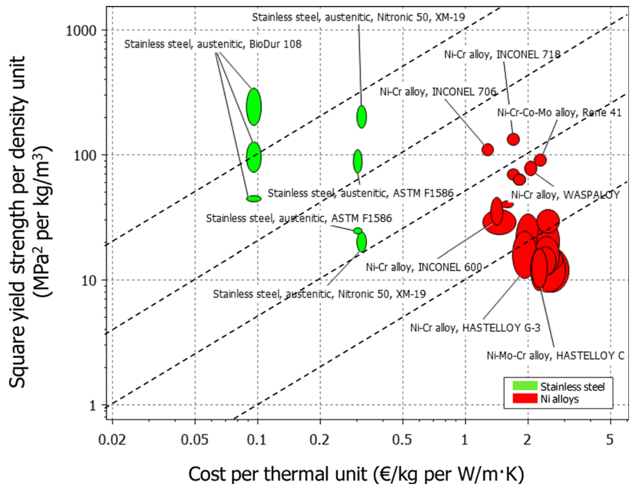

Fig. 6 Specific strength vs. cost per thermal unit for different alloys, obtained with CES Selector, with the long-term selection criteria

has only been tested at room temperature. The third material is ASTM CA40, which is an iron-chromium alloy with good corrosion resistance used in steam turbine parts, among other applications.

3.3 Long-Term Selection Case Study

When the most important criterion for the selection of materials is the lifetime of the superheater tubes, then the material must have an excellent durability in strong acid media, while cost and thermal conditions are not considered so closely. Therefore, the constraints become:

(i) Yield strength ≥ 400 MPa.
(ii) Maximum service temperature ≥ 400 °C.
(iii) Durability in strong acid media: excellent.

Table 4 summarizes the main mechanical and thermal properties involved in the selection process for the best candidates that fulfill all the long-term selection criteria. As shown in Fig. 6 and Table 4, Ni-based alloys and some of specific austenitic stainless steels are the best candidates for long-term selection, due to their excellent durability in strong acid media. The austenitic stainless steels, such as BioDur 108, Nitronic 50 (XM-19), and ASTM F1586, present the highest performance indices. Ni-alloys present lower thermal conductivities than stainless steels and their prices are also higher, this makes their costs per thermal unit higher than for stainless steels. However, their maximum service temperatures are higher, thus indicating that mechanical properties would be maintained up to higher temperatures, thereby extending their lifetime. Among the Ni-based alloys selected, INCONEL 706 presents the highest material index, which is achieved with a thermal conductivity of 12-13 W/m K and a relatively acceptable price (14.9-16.3 €/kg) compared to other Ni-alloys (Ref 44, 45; Table 4).

Before selecting the material with the highest performance, it is necessary to browse the literature in order to find possible uses of this material, details of its properties, availability and pricing, as well as commercialized shapes. BioDur 108 is essentially a nickel-free stainless steel alloy designed for medical implants. It offers excellent resistance to pitting and crevice corrosion at room temperature (Ref 43). Nitronic 50 (XM-19) is a nitrogen-strengthened austenitic stainless steel that provides very good resistance to corrosion, an excellent combination of strength, ductility, and toughness, even at cryogenic temperatures (Ref 46). It has been used in applications such as pumps and fittings for chemical equipment, fasteners, cables, chains, screens, and marine hardware. It is available in the following forms: seamless pipe, welded pipe, seamless tube, welded tube, bar, wire, sheet, plate, forgings, pipe fittings, and flanges. ASTM F1586 (BioDur 734 alloy) is another wrought nitrogen-strengthened stainless steel for surgical implants. Both stainless steels are used in medical applications, so their corrosion resistances have been tested only at room temperature. Most of these materials have a decrease in their corrosion resistance as well as in their mechanical properties as the temperature increases. In this case, as no information about the behavior of these nickel-free stainless steels can be found in the literature, we must reject them and keep Nitronic 50 (XM-19) stainless steel as the best selection for the described purpose.

4. Conclusions

The proposed methodology allows us to evaluate the performance of different materials to be used as MSWI superheater tubes. The proposed materials can operate at steam pressures and temperatures higher than 40 bars and 400 °C, respectively. Two case studies are presented: the first taking into account a balanced selection between mechanical properties and cost per thermal unit; the other focusing on increased lifetime.

The use of a material index leads to the selection of materials that perform a certain function better. Nevertheless, it is important to look at the data in the literature before taking a decision. Nickel-free stainless steel alloys are a case in point; they are used as medical implants and present high corrosion resistance, but have not been tested at high temperatures.

The balanced selection shows that AISI 410 martensitic stainless steel (wrought, hard tempered) would be the best candidate with a good combination of corrosion resistance, a relatively low price (0.83-0.92 €/kg) and good thermal conductivity (23-27 W/m K). However, Nitronic 50/XM-19 stainless steel is the most promising candidate for a long-term selection, as it presents high corrosion resistance at a relatively low price (4.86-5.14 €/kg) compared to Ni-alloys.

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