



(12) **EUROPEAN PATENT APPLICATION**

(43) Date of publication:
02.03.2022 Bulletin 2022/09

(21) Application number: **20193794.3**

(22) Date of filing: **01.09.2020**

(51) International Patent Classification (IPC):

C21D 6/00 (2006.01)	C22C 38/00 (2006.01)
C22C 38/44 (2006.01)	C22C 38/02 (2006.01)
C22C 38/04 (2006.01)	C22C 38/42 (2006.01)
C22C 38/46 (2006.01)	C22C 38/58 (2006.01)
C21D 9/46 (2006.01)	

(52) Cooperative Patent Classification (CPC):

C21D 6/004; C22C 38/001; C22C 38/02;
C22C 38/04; C22C 38/44; C21D 9/46;
C21D 2211/001; C22C 38/42; C22C 38/58

(84) Designated Contracting States:
AL AT BE BG CH CY CZ DE DK EE ES FI FR GB
GR HR HU IE IS IT LI LT LU LV MC MK MT NL NO
PL PT RO RS SE SI SK SM TR
Designated Extension States:
BA ME
Designated Validation States:
KH MA MD TN

(71) Applicant: **Outokumpu Oyj**
00180 Helsinki (FI)

(72) Inventors:
• **Oliver, James**
749 72 Fjärdhundra (SE)
• **Jonsson, Jan Y.**
77554 Krylbo (SE)

(54) **AUSTENITIC STAINLESS STEEL**

(57) Austenitic stainless steel utilizing the TRIP effect with a balanced pitting resistance equivalent for high corrosion resistance. The austenitic stainless steel contains 0-0.04 weight % C, 0.2-0.8 weight % Si, 0-2.0 weight % Mn, 16.0-19.0 weight % Cr, 4.0-6.5 weight % Ni, 1.0-4.0 weight % Mo, 0-4.0 weight % W, 0-2.0 weight % Cu,

0.20-0.30 weight % N, the rest being iron and inevitable impurities occurring in stainless steels, the proportion of the ferrite phase in the microstructure is 0-10.0 volume %, the rest being austenite, when quenched and heat treated at the temperature range of 900 - 1200 °C, preferably 950 - 1150 °C.

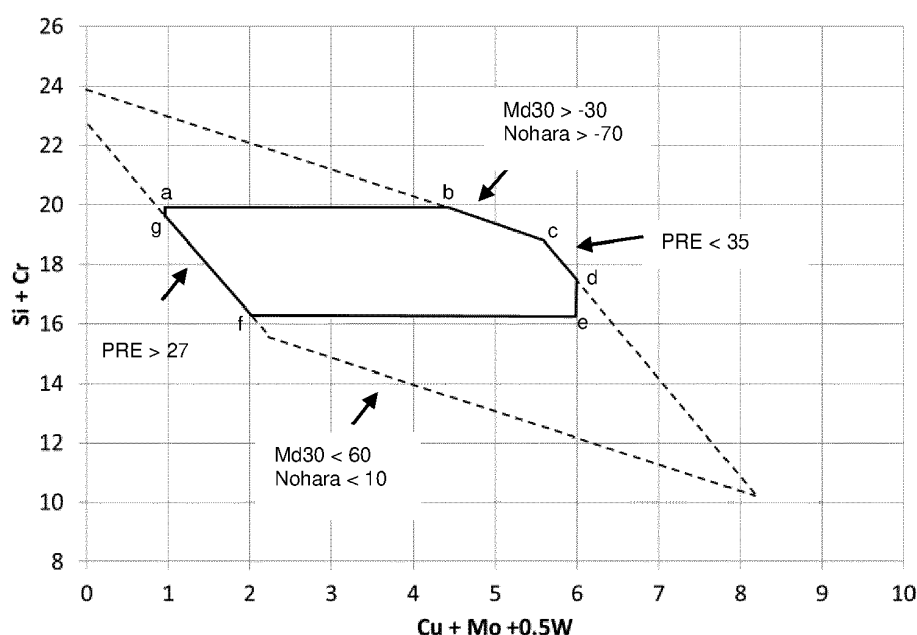


Fig. 1

Description

[0001] This invention relates to an austenitic stainless steel which has high formability with the TRIP (Transformation Induced Plasticity) effect and high corrosion resistance and optimized pitting resistance equivalent (PRE).

[0002] The transformation induced plasticity (TRIP) effect refers to the transformation of metastable retained austenite to martensite during plastic deformation as a result of imposed stress or strain. This property allows stainless steels having the TRIP effect to have a high formability, while retaining excellent strength.

[0003] It is well known from patent application WO 2015/114222 a method for manufacturing a ferritic-austenitic stainless steel having good formability and high elongation, which steel contains in weight % less than 0,04 weight % carbon, 0,2 - 0,8 weight % silicon, less than 2,0 weight % manganese, 16,5 - 19,5 weight % chromium, 3,0 - 4,7 weight % nickel, 1,0 - 4,0 weight % molybdenum, less than 3,5 weight % tungsten, less than 1 weight % copper, 0,13 - 0,26 weight % nitrogen, the rest being iron and inevitable impurities occurring in stainless steels. Sulphur is limited to less than 0,010 weight % and preferably less than 0,005 weight %, the phosphorus content is less than 0,040 weight % and the sum of sulphur and phosphorus (S+P) is less than 0,04 weight %, and the total oxygen content is below 100 ppm. The aluminium content is maximized to less than 0,04 weight % and preferably the maximum is less than 0,03 weight %. Further, boron, calcium and cerium are optionally added in small quantities; the preferred contents for boron and calcium are less than 0,004 weight % and for cerium less than 0,1 weight %. Optionally cobalt can be added up to 1 weight % for partial replacement of nickel. Also one or more of the group containing niobium, titanium and vanadium can be optionally added in the stainless steel of the invention, the contents of niobium and titanium being limited up to 0,1 weight % and the vanadium content being limited up to 0,2 weight %.

[0004] According to the WO patent application 2015/114222 the pitting resistance equivalent (PRE) has been optimized to give good corrosion resistance, being in the range of 30-36. The critical pitting temperature (CPT) is in the range of 34-45°C. Heat treatment is performed so that the microstructure of the stainless steel contains 45 - 80 % austenite in the heat treated condition, the remaining microstructure being ferrite. Further, the measured M_{d30} temperature of the stainless steel is adjusted between -30 and 90°C, preferably in the range 10-60°C in order to utilize the TRIP effect for improving the formability of the stainless steel.

[0005] It is known from the WO patent application 2011/135170 a method for manufacturing a ferritic-austenitic stainless steel having good formability and high elongation, which steel contains in weight % less than 0,05 % C, 0,2-0,7 % Si, 2-5 % Mn, 19-20,5 % Cr, 0,8-1,35 % Ni, less than 0,6 % Mo, less than 1 % Cu, 0,16-0,24 % N, the balance being iron and inevitable impurities. The stainless steel of the WO patent application 2011/135170 is heat treated so that the microstructure of the stainless steel contains 45 - 75 % austenite in the heat treated condition, the remaining microstructure being ferrite. Further, the measured M_{d30} temperature of the stainless steel is adjusted between 0 and 50 °C in order to utilize the TRIP effect for improving the formability of the stainless steel.

[0006] Furthermore, it is known from the WO patent application 2013/034804 a ferritic austenitic stainless steel utilizing the TRIP effect, which contains less than 0,04 weight % C, less than 0,7 weight % Si, less than 2,5 weight % Mn, 18,5-22,5 weight % Cr, 0,8-4,5 weight % Ni, 0,6-1,4 weight % Mo, less than 1 weight % Cu, 0,10-0,24 weight % N, the rest being iron and inevitable impurities occurring in stainless steels. Sulphur is limited to less than 0,010 weight % and preferably less than 0,005 weight %, the phosphorus content is less than 0,040 weight % and the sum of sulphur and phosphorus (S+P) is less than 0,04 weight %, and the total oxygen content is below 100 ppm. The stainless steel optionally contains one or more added elements in the following: the aluminium content is maximized to less than 0,04 weight % and preferably the maximum is less than 0,03 weight %. Further, boron, calcium and cerium are optionally added in small quantities; the preferred contents for boron and calcium are less than 0,003 weight % and for cerium less than 0,1 weight %. Optionally cobalt can be added up to 1 weight % for partial replacement of nickel, and tungsten can be added up to 0,5 weight % as partial replacement of molybdenum. Also one or more of the group containing niobium, titanium and vanadium can be optionally added in the stainless steel of the invention, the contents of niobium and titanium being limited up to 0,1 weight % and the vanadium content being limited up to 0,2 weight %.

[0007] According to the WO patent application 2013/034804 the pitting resistance equivalent (PRE) has been optimized to give good corrosion resistance, being in the range of 27-29,5. The critical pitting temperature (CPT) is in the range of 20-33 °C, preferably 23-31 °C. The TRIP (Transformation Induced Plasticity) effect in the austenite phase is maintained in accordance with the measured M_{d30} temperature at the range of 0-90°C, preferably in the range of 10-70°C, in order to ensure the good formability. The proportion of the austenite phase in the microstructure of the stainless steel of the invention is in the heat treated condition 45-75 volume %, advantageously 55-65 volume %, the rest being ferrite, in order to create favourable conditions for the TRIP effect. The heat treatment can be carried out using different heat treatment methods, such as solution annealing, high-frequency induction annealing or local annealing, at the temperature range from 900 to 1200 °C, preferably from 950 to 1150°C.

[0008] Japanese patent application 2014001422A, shows an austenitic stainless steel with composition in mass%, C: 0.02 to 0.30%, Cr: 10.0 to 25.0%, Ni: 3.5 to 10.0%, Si: 0.1 to 3.0%, Mn: 0.5% to 5.0%, N: 0.10 to 0.40%, Mo: 0 to 3.0%, Cu: 0 to 3.0%, Ti: 0 to 0.10%, Nb: 0 to 0.50%, V: 0 to 1.0%, with a calculated M_{d30} of 0-40 based on a formula very

similar to Nohara. The chemical range is very wide but the examples given in the invention show predominantly low levels of Mo and N which give a low PRE and corrosion resistance. The invention shows that austenitic alloys with a balanced Ni and N content can have a low stability but this is done only with a low PRE and corrosion resistance due to low Mo and in reality the real M_{d30} is likely to be much higher than the claimed region.

[0009] The present invention describes a new austenitic stainless steel utilizing the TRIP effect described in the prior art with an addition of a high pitting resistance equivalent (PRE) and giving therefore superior corrosion resistance combined with a TRIP effect with improved formability. In comparison to other commercially available austenitic stainless steels such as TRIP 301 and slightly more stable 304 the new invention has a PRE and corrosion resistance that is far superior. In comparison to 316, the TRIP effect and PRE is substantially higher. In comparison to 904L the PRE and corrosion resistance of the invention is up to a similar level, but with a far superior TRIP effect that is not otherwise observed in any other high alloyed austenitic stainless steel. In addition to all of the reference alloys mentioned, the new invention has a much leaner composition in particular considering the Ni-content. This gives the invention a unique combination of high corrosion, TRIP and a cost effective alternative. The essential features of the invention are enlisted in the appended claims.

[0010] According to the invention, the austenitic stainless steel contains less than 0,04 weight % C, 0,2-0,8 weight % Si, 0-2,0 weight % Mn, 16,0-19,0 weight % Cr, 4,0-6,5 weight % Ni, 1,0-4,0 weight % Mo, 0-4,0 weight % W, 0-2,0 weight % Cu, 0,20-0,30 weight % N, the rest being iron and inevitable impurities occurring in stainless steels. Sulphur is limited to less than 0,010 weight % and preferably less than 0,005 weight %, the phosphorus content is less than 0,040 weight % and the sum of sulphur and phosphorus (S+P) is less than 0,04 weight %, and the total oxygen content is below 100 ppm.

[0011] The austenitic stainless steel of the invention optionally contains one or more added elements in the following: the aluminium content is maximized to less than 0,04 weight % and preferably the maximum is less than 0,03 weight %. Further, boron, calcium and cerium are optionally added in small quantities; the preferred contents for boron and calcium are less than 0,004 weight % and for cerium less than 0,1 weight %. Optionally cobalt can be added up to 1 weight % for partial replacement of nickel. Also one or more of the group containing niobium, titanium and vanadium can be optionally added in the austenitic stainless steel of the invention, the contents of niobium and titanium being limited up to 0,1 weight % and the vanadium content being limited up to 0,2 weight %.

[0012] According to the stainless steel of the invention, the pitting resistance equivalent (PRE) has been optimized to give good corrosion resistance, being at the range of 27-35. The critical pitting temperature (CPT) is in the range of 30-50°C. The TRIP (Transformation Induced Plasticity) effect in the austenite phase is maintained in accordance with the calculated M_{d30} temperature at the range of - 70°C to +60°C. The M_{d30} -temperature, which is a measure for the austenite stability to the TRIP effect, is defined as the temperature at which 0,3 true strain yields 50% transformation of the austenite to martensite. In addition, the stacking fault energy of the invented stainless steels is much lower than commercially available stainless steels and is between 10-16mJ/m² according to formula (3). The proportion of the ferrite phase in the microstructure of the austenitic stainless steel of the invention is in the heat treated condition <10 volume %. The heat treatment can be carried out using different heat treatment methods, such as solution annealing, high-frequency induction annealing, local annealing or any other type of heat treatment at the temperature range from 900 to 1200 °C, preferably from 950 to 1150°C.

[0013] Effects of different elements in the microstructure are described in the following, the element contents being described in weight %:

Carbon (C) partitions to the austenite phase and has a strong effect on austenite stability. Carbon can be added up to 0,04 % but higher levels have detrimental influence on corrosion resistance.

[0014] Nitrogen (N) is an important austenite stabilizer in stainless steels and like carbon it increases the stability against martensite. Nitrogen also increases strength, strain hardening and corrosion resistance. The general empirical expressions on the M_{d30} temperature indicate that nitrogen and carbon have the same strong influence on austenite stability, but this is lower than previously reported in other M_{d30} expressions. Because nitrogen can be added to stainless steels in larger extent than carbon without adverse effects on corrosion resistance the nitrogen contents from 0,20 up to 0,30 % are effective in present stainless steels.

[0015] Silicon (Si) is normally added to stainless steels for deoxidizing purposes in the melt shop and should not be below 0,2 %. Silicon has a stronger stabilizing effect on austenite stability against martensite formation than shown in current expressions. For this reason silicon is maximized to 0,8 %, preferably to 0,5 %.

[0016] Manganese (Mn) is an important addition to stabilize the austenite phase and to increase the solubility of nitrogen in the stainless steel. Manganese can partly replace the expensive nickel and bring the stainless steel to the right phase balance. Too high level in the content will reduce the corrosion resistance. Manganese has a stronger effect on austenite stability against deformation martensite and, therefore, the manganese content must be carefully addressed. The range of manganese shall be 0-2,0 %, preferably 0-1,5 %.

[0017] Chromium (Cr) is the main addition to make the steel resistant to corrosion. Further, chromium strongly increases the resistance to martensite formation and, therefore, reduces the TRIP effect. Also being a strong ferrite stabilizer the level of Cr needs to be limited in the austenitic stainless steel. To bring about these functions the chromium level should

be at least 16.0% and the maximum level 19.0%. Preferably the chromium content is 16,5-18,7%

[0018] Nickel (Ni) is an essential alloying element for stabilizing the austenite phase and for good ductility and at least 4,5 % must be added to the stainless steel of the invention. Having a large influence on austenite stability against martensite formation nickel has to be present in a narrow range. Ni also has a significant influence on increasing the stacking fault energy of stainless steels. Further, because of nickel's high cost and price fluctuation nickel should be maximized in the stainless steel of the invention to 6,5 %, preferably to 6,2%

[0019] Copper (Cu) is normally present as a residual of 0,1-0,5 % in most stainless steels, when the raw materials to a great deal are in the form of stainless scrap containing this element. Copper is a weak stabilizer of the austenite phase but has a strong effect on the resistance to martensite formation and must be considered in evaluation of formability of the present stainless steels. An intentional addition up to 2,0 % can be made, but preferably the copper content is up to 1,6 %.

[0020] Molybdenum (Mo) be added to significantly increase the PRE and corrosion resistance and, therefore, molybdenum shall have a content at least 1,0 %, preferably at least 1,5 %. Further it has been found that, molybdenum, like chromium, strongly increases the resistance to martensite formation and reduces the TRIP effect significantly more than previous expected. Therefore, molybdenum cannot be added to more than 4,0.

[0021] Tungsten (W) has similar properties as molybdenum and can sometimes replace molybdenum. However, tungsten and molybdenum promote sigma phase precipitation and the sum of the molybdenum and tungsten contents according to the formula $(Mo + 0,5W)$ should be 0-4,0 %, preferably 2,0 - 4,0 %, where the promotion of sigma and chi phases are possible to handle in technically relevant processes. The most important influence of tungsten is the surprisingly positive impact on the TRIP effect which in turn could be related to the effect on the stacking fault energy of the alloy since the stacking fault energy controls the deformation response in terms of dislocation glide, twinning or martensite formation. For this purpose, tungsten should be limited up to 3,8 %, but preferably at least 1,0 % when tungsten is used to replace molybdenum. Boron (B), calcium (Ca) and cerium (Ce) are added in small quantities in austenitic steels to improve hot workability and not at too high contents as this can deteriorate other properties. The preferred contents for boron and calcium in the stainless steel of the invention are less than 0,004 % and for cerium less than 0,1 %.

[0022] Sulphur (S) in austenitic steels deteriorates hot workability and can form sulphide inclusions that influence pitting corrosion resistance negatively. The content of sulphur should therefore be limited to less than 0,010 % and preferably less than 0,005 %.

[0023] Phosphorus (P) deteriorates hot workability and can form phosphide particles or films that influence corrosion resistance negatively. The content of phosphorus should therefore be limited to less than 0,040 %, and so that the sum of sulphur and phosphorus (S+P) contents is less than 0,04 %.

[0024] Oxygen (O) together with other residual elements has an adverse effect on hot ductility. The presence of oxide inclusions may reduce corrosion resistance (pitting corrosion) depending on type of inclusion. High oxygen content also reduces impact toughness. In a similar manner as sulphur oxygen improves weld penetration by changing the surface energy of the weld pool. For the stainless steel of the invention the advisable maximum oxygen level is below 100 ppm. In a case of a metallic powder the maximum oxygen content can be up to 250 ppm.

[0025] Aluminium (Al) should be kept at a low level in the austenitic stainless steel of the invention with high nitrogen content as these two elements can combine and form aluminium nitrides that will deteriorate the impact toughness. The aluminium content is limited to less than 0,04 % and preferably to less than 0,03 %.

[0026] Cobalt (Co) has similar metallurgical behaviour as its sister element, nickel, and cobalt may be treated in much the same way in steel and alloy production. Cobalt inhibits grain growth at elevated temperatures and considerably improves the retention of hardness and hot strength. Cobalt increases the cavitation erosion resistance and the strain hardening. Cobalt reduces the risk of sigma phase formation in stainless steels. The cobalt content is limited up to 1,0 %.

[0027] The "micro-alloying" elements titanium (Ti), vanadium (V) and niobium (Nb) belong to a group of additions so named because they significantly change the steels properties at low concentrations, often with beneficial effects in carbon steel but in the case of austenitic stainless steels they also contribute to undesired property changes, such as reduced impact properties, higher surface defects levels and reduced ductility during casting and hot rolling. Many of these effects depend on their strong affinity for carbon and in particular nitrogen in the case of modern austenitic stainless steels. In the present invention niobium and titanium should be limited to maximum level of 0,1% whereas vanadium is less detrimental and should be less than 0,2%.

[0028] The present invention is described in more details referring to the drawings, of which

Figure 1 illustrates the dependence of the minimum and maximum M_{d30} temperature and PRE values between the element contents Si+Cr and Cu+Mo+0,5W in the tested alloys of the invention,

Figure 2 illustrates an example with constant values of C+N and Mn+Ni for the dependence of the minimum and maximum M_{d30} temperature and PRE values between the element contents Si+Cr and Cu+Mo+0,5W in the tested alloys of the invention according to Fig. 1,

Figure 3 illustrates the dependence of the minimum and maximum M_{d30} temperature, PRE and SFE values between the element contents C+N and Mn+Ni in the tested alloys of the invention. Figure 4 illustrates an example with constant values of Si+Cr and Cu+Mo+0.5W for the dependence of the minimum and maximum M_{d30} temperature, PRE and SFE values between the element contents C+N and Mn+Ni in the tested alloys of the invention according to Fig. 3.

[0029] In all Figures 1-4, the M_{d30} limiting values given are the preferred limiting values of the invention calculated in accordance with a mathematical constraint of optimization used in this invention. These calculated M_{d30} values are given in table 2 for all the alloys. In addition, the limiting Nohara M_{d30} values are also given in the figures for reference and comparison.

[0030] Figures 5-7 show the microstructures of some of the alloys after annealing at 1100°C followed by water quenching. Figure 5 and Figure 7 shows the microstructure of two of the invented alloys, showing how the observed level of martensite is related to the calculated M_{d30} value of the invention. Also shown is the low ferrite content illustrating that the invented alloys are considered to be fully austenitic. Figure 6 is from reference alloy UNS S30403 for comparison purposes.

[0031] Based on the effects of the elements the austenitic stainless steel according to the invention is presented with the chemical compositions A to S as named in table 1. Table 1 contains also the typical chemical composition for the reference commercially available austenitic stainless steels named as T to X, all the contents of the table 1 in weight %.

Table 1

Alloy	UNS number	C %	Si %	Mn %	Cr %	Ni %	Cu %	N %	Mo %	W %
A	-	0.03	0.484	0.75	17.61	4.5	0.43	0.253	1.98	
B	-	0.03	0.484	0.75	17.61	4.39	0.43	0.253	1.1	1.9
C	-	0.025	0.484	0.5	17.61	4.8	0.43	0.253	1.98	
D	-	0.025	0.48	0.5	17.61	5	0.43	0.26	1.98	
E	-	0.025	0.48	0.39	17.51	4.7	0.2	0.246	1.84	
F	-	0.025	0.48	0.39	18.5	5.5	0.4	0.26	2.2	
G	-	0.022	0.62	0.4	18.65	6.03	0.4	0.23	2.19	
H	-	0.026	0.62	0.4	18.41	5.05	1.42	0.22	2.21	
I	-	0.025	0.4	1.5	18	5.3	1.5	0.28	2.4	
J	-	0.026	0.42	1.65	18.18	5.52	1.56	0.273	2.39	
K	-	0.025	0.55	0.5	17.2	5	0.45	0.26	3.11	
L	-	0.025	0.45	1.3	17	4.5	1.5	0.26	3.3	
M	-	0.022	0.58	1.32	16.97	4.69	1.47	0.293	3.36	
N	-	0.022	0.58	1.32	16.97	4.69	1.47	0.293	1.6	3.4
O	-	0.025	0.45	1.7	16.8	5.2	1.5	0.29	3.3	
P	-	0.023	0.485	1.8	16.77	5.29	1.47	0.218	3.32	
Q	-	0.023	0.5	1.4	17.2	6	1.4	0.29	3.7	
R	-	0.023	0.5	1.5	16.5	6.2	1	0.29	3.9	
S	-	0.023	0.5	1.5	16.5	6.2	1	0.29	2.1	3.75
T	UNS S30403	0.021	0.35	1.5	18	8	0.3	0.06	0.3	
U	UNS S31603	0.021	0.35	1.5	18	10	0.3	0.06	2.5	
V	UNS S31655	0.025	0.45	1.8	20	8.5	0.5	0.19	0.6	
W	UNS N08904	0.015	0.35	1.75	20	25	1.5	0.06	4.5	
X	UNS S30100	0.05	0.5	1	17	7		0.05	0.3	

[0032] The alloys A - S were manufactured in an induction furnace in 1 kg laboratory scale to small slabs.

The referred alloys T and X were produced in 100 ton production scale followed by hot rolling and cold rolling to coil form with varying final dimensions.

[0033] When comparing the values in the Table 1 the contents of, nickel, nitrogen and tungsten in the austenitic stainless steels of the invention are significantly different from the reference stainless steels T to X and R.

[0034] The properties, the values for the M_{d30} temperature, the critical pitting temperature (CPT), Pitting Resistant Equivalent PRE and Stacking Fault Energy (SFE) were determined for the chemical compositions of the table 1 and the results are presented in the following table 2.

[0035] The predicted M_{d30} temperature (M_{d30} Nohara) of the steels in the table 2 was calculated using the Nohara expression (1) established for austenitic stainless steels

$$M_{d30} = 551 - 462(C+N) - 9,2Si - 8,1Mn - 13,7Cr - 29(Ni+Cu) - 18,5Mo - 68Nb \quad (1),$$

when annealed at the temperature of 1050 °C.

[0036] The calculated M_{d30} temperatures in the table 2 were achieved in accordance with a mathematical constraint of optimization.

[0037] The critical pitting temperature (CPT) is measured in a 1M sodium chloride (NaCl) solution according to the ASTM G150 test, and below this critical pitting temperature (CPT) pitting is not possible and only passive behaviour is seen.

[0038] The pitting resistance equivalent (PRE) is calculated using the formula (2):

$$PRE = \%Cr + 3,3(\%Mo + 0,5\%W) + 16N \quad (2)$$

[0039] The sums of the element contents for C+N, Cr+Si, Cu+Mo+0,5W and Mn+Ni in weight % are also calculated for the alloys of the table 1 in the table 2. The sums C+N and Mn+Ni represent austenite stabilizers, while the sum Si+Cr represents ferrite stabilizers and the sum Cu+Mo+0,5W elements having resistance to martensite formation.

Alloy	UNS number	C+N %	Si+Cr %	Mn+Ni %	Cu+Mo +0,5W %	Calc M_{d30} °C	M_{d30} Nohara °C	SFE mJ/m ²	CPT °C	PRE
A	-	0.283	18.09	2.41	5.25	38.7	-7.9	11.25	31.8	28.2
B	-	0.283	18.09	2.48	5.14	39.2	8.3	10.37	32.3	28.4
C	-	0.278	18.09	2.41	5.3	38.2	-15.5	11.50	31.8	28.2
D	-	0.285	18.09	2.41	5.5	33.4	-24.5	11.86	32.1	28.3
E	-	0.271	17.99	2.04	5.09	56.1	2.2	11.18	30.0	27.5
F	-	0.285	18.98	2.6	5.89	-5.7	-53.5	12.92	36.2	29.9
G	-	0.252	19.27	2.59	6.43	-22.0	-56.9	13.50	35.4	29.6
H	-	0.246	19.03	3.63	5.45	-21.8	-52.3	11.85	34.4	29.2

I	-	0.305	18.4	3.9	6.8	-44.5	-93.9	13.41	37.5	30.4
J	-	0.299	18.6	3.95	7.17	-58.8	-103.0	13.90	35.0	30.4
K	-	0.285	17.75	3.56	5.5	12.6	-41.0	12.54	40.6	31.6
L	-	0.285	17.45	4.8	5.8	-18.1	-63.3	12.43	41.9	32.1
M	-	0.315	17.55	4.83	6.01	-29.1	-83.8	12.23	43.4	32.7
N	-	0.315	17.55	4.77	6.01	-27.5	-51.3	10.87	42.9	32.5
O	-	0.315	17.25	4.8	6.9	-38.2	-97.9	13.85	42.4	32.3
P	-	0.241	17.26	4.79	7.09	-35.0	-66.6	14.17	39.5	31.2
Q	-	0.313	17.7	5.1	7.4	-69.5	-128.2	15.30	47.0	34.1
R	-	0.313	17	4.9	7.7	-49.9	-117.4	15.90	46.7	34.0
S	-	0.313	17	4.97	7.7	-52.1	-84.1	14.51	47.8	34.4
T	UNS S30403	0.081	18.35	0.6	9.5	9.9	5.3	17.82	<10	20.0
U	UNS S31603	0.081	18.35	2.8	11.5	-90.7	-93	22.97	20	26.6
V	UNS S31655	0.215	20.45	1.1	10.3	-94.0	-113	18.40		25.9
W	UNS N08904	0.075	20.35	6	26.7 5	-552	-627	53.13	58	35.8
X	UNS S30100	0.1	17.5	0.6	8	77	51	16.33	<10	18.8

Table 2.

[0040] When comparing the values in the Table 2 the PRE value of for alloys A-S having the range of 27-35 is higher than the PRE value in the referred stainless steels T-V which means that the corrosion resistance of the alloys A - S is higher. The critical pitting temperature CPT is in the range of 31 - 48 °C, which is a high level of corrosion resistance and much higher than the CPT for the referred austenitic stainless steels T to V.

[0041] The predicted M_{d30} temperatures using the Nohara expression (1) agree well with the known M_{d30} for the reference alloys T-V, but are not considered to be accurate for the inventive alloys A to S. This is because the inventive alloys A-S have a chemical composition unique from the austenitic steels that the Nohara expression was originally derived. In particular, the effect of N on the austenite stability and M_{d30} , although still high has been found to be considerably lower in these inventive steels. The Nohara expression was originally derived for austenitic steels with low N and therefore the total effect of nitrogen in those steels was little. In the current invention, to increase the austenitic content, given that the Ni is low, and to have a high corrosion resistant stainless steel, i.e. increase the PRE, the N content is much higher than in the alloys. According to Nohara this would make the inventive steels very stable. The majority of the steels A-S have -50 or lower when using the M_{d30} expression of Nohara. The evaluation of the microstructure of steels A-S in this invention, together with previous prior art knowledge of measured M_{d30} values of alloys with similar composition levels in stainless steels as in WO patent application 2015/114222, has shown that the M_{d30} of alloys A-S are higher than predicted by Nohara. As such, a new M_{d30} expression has been derived for the invented alloys. As can be seen in table 2 the calculated M_{d30} values for the reference alloys agree very well with the predicted values using Nohara, which also agree with the known real measured values for these commercially available grades. The new expression therefore is a good measure of the M_{d30} even for low N-contained stainless steel grades. In Figure 5, a microstructure image is presented for alloy E. The microstructure of this alloy shows a considerably amount of martensite after annealing at 1100°C followed by water quenching, which is consistent with an M_{d30} of +56 as given by the calculated M_{d30} for this invention, but not consistent with the Nohara M_{d30} of 2. An alloy with an M_{d30} of 2 as predicted by Nohara for Alloy E would be expected, by anyone skilled in the art, to be essentially martensite free with the above describe annealing and quenching conditions. For example, Figure 6 shows the as-quenched microstructure of reference Alloy T (UNS S30403), remelted to give an equivalent cast microstructure and Alloy E. This microstructure shows no, or at least very little martensite, which is expected for this commercially available grade with an M_{d30} of 0-10 predicted by both Nohara and the calculated M_{d30} of this invention. These two examples show that the new M_{d30} calculation gives a better description of the true stability and M_{d30} values of all alloys than the Nohara expression and thus are the basis of the claimed calculated M_{d30} limits of this invention.

[0042] Figure 7 shows the microstructure of alloy P which has a calculated M_{d30} of -35 and as seen no evidence of

martensite in the as-quenched condition. Additionally, when observing the microstructures of Figure 5 and Figure 7, it is noted that the austenite content is high and that the remaining ferrite content is less than 10%. Fully austenitic stainless steels typically have a ferrite content of up to 10% as illustrated by the microstructure of Figure 6 for Alloy T. These examples show that the alloys with higher and lower calculated M_{d30} (-70°C to $+60^{\circ}\text{C}$) have an austenitic microstructure equivalent to the reference alloy T.

[0043] The stacking fault energies were calculated using the formula (3) of G. Meric de Bellefon, J. C. van Duysen, and K. Sridharan, "Composition-dependence of stacking fault energy in austenitic stainless steels through linear regression with random intercepts," J. Nucl. Mater., vol. 492, for austenitic stainless steels.

$$\text{SFE (mJ/m}^2\text{)} = 2.2 + 1.9\text{Ni} - 2.9\text{Si} + 0.77\text{Mo} + 0.5\text{Mn} + 40\text{C} - 0.016\text{Cr} - 3.6\text{N} \quad (3)$$

[0044] The stacking fault energies (SFE) of the austenitic stainless steels of the invention are lower than the commercially available austenitic stainless steel. The SFE of the reference alloys, T and X, that are relatively low alloyed with a low PRE (<27) and consequently a higher M_{d30} , >0 is greater than 16 mJ/m^2 . In addition the SFE for the higher alloyed and high PRE (>35) with low M_{d30} (<-70) grade 904L is also greater than 16 mJ/m^2 . Alloys A to S of the invention are unique in the sense that all have SFE lower than 16 mJ/m^2 whilst having a PRE between 27-35 and an M_{d30} between -70 to $+60$.

[0045] The sums of the element contents for C+N, Si+Cr, Mn+Ni and Cu+Mo+0,5W in weight % for the austenitic stainless steel of the present invention were used in the mathematical constraint of optimization to establish the dependence in one hand between C+N and Mn+Ni, and in another hand between Si+Cr and Cu+Mo+0,5W. In accordance with this mathematical constraint of optimization the sums of Cu+Mo+0,5W and Si+Cr, respectively the sums Mn+Ni and C+N, form the x and y axis of a coordination in the Figs. 1-4 where the linear dependence for the minimum and maximum PRE values ($27 < \text{PRE} < 35$) and for the minimum and maximum M_{d30} temperature ($-30 < M_{d30} < 60$) values are defined. In accordance with Fig. 1 a chemical composition window for Si+Cr and Cu+Mo+0,5W is established with the preferred ranges of 0,21-0,33 for C+N and 4,0-7,7 for Mn+Ni. It is also noticed in Fig. 1 that the sum Si+Cr is limited to $16,2 < \text{Si+Cr} < 19,8$ and the sum of Cu+Mo+0,5W is limited to $1,0 < \text{Cu+Mo+0,5W} < 6,0$ in accordance with the stainless steel of the invention. The chemical composition window, which lies within the frame of the area a', b', c', d', e', f' and g' in Fig. 1, is defined with the following labelled positions of the coordination in the table 3.

Table 3

	Si+Cr %	Cu+Mo+0,5W %	C+N%	Mn+Ni %
a'	19,8	1,0	0,24	8,5
b'	19,8	4,4	0,21	4,0
c'	18,8	5,6	0,21	4,0
d'	17,4	6,0	0,21	5,5
e'	16,2	6,0	0,30	4,0
f'	16,2	2,1	0,33	6,2
g	19,6	1,0	0,28	6,2

[0046] Fig 1 shows that the composition ranges of the invention for Si+C and Cu+Mo+0,5W are further limited by the constraint of the $27 < \text{PRE} < 35$ and a calculated $M_{d30} > -30$ (alternatively Nohara $M_{d30} < -70$) when the composition limits for C+N and Ni+Mn are within the preferred limits of the invention.

[0047] Fig. 2 illustrates one chemical composition example window of Fig. 1 when constant values of 0,295 for C+N and 6,0 for Mn+Ni are used at all points instead of the preferred ranges for C+N and Mn+Ni in Fig. 1. The same limitations of the invention are given to the sum of Si+Cr and Cu+Mo+0,5W in Fig. 2 as in Fig. 1. The chemical composition window, which lies within the frame of the area a, b, c, d, e, f and g in Fig. 2, is defined with the following labelled positions of the coordination in the table 4.

Table 4

	Si+Cr %	Cu+Mo+0,5W %	C+N %	Mn+Ni %
a	19,8	1,0	0.295	6.0

(continued)

	Si+Cr %	Cu+Mo+0,5W %	C+N %	Mn+Ni %
b	19,8	2,5	0,295	6,0
c	18,3	4,3	0,295	6,0
d	16,2	4,9	0,295	6,0
e	16,2	2,75	0,295	6,0
f	17,2	1,5	0,295	6,0
g	19,1	1,0	0,295	6,0

[0048] Fig 2 shows that that the composition ranges of the invention for Si+C and Cu+Mo+0,5W are limited even more when specific constant levels of C+N and Mn+Ni are given. In addition to the constraints in Fig 1, the composition window is also limited by the line of the calculated $M_{d30} < 60$ (alternatively Nohara < 10)

[0049] Fig. 3 illustrates a chemical composition window for C+N and Mn+Ni with the preferred composition ranges 16,5-19,5 for Cr+Si and 2,2-5,7 for Cu+Mo+0,5W, when the austenitic stainless steel was annealed at the temperature of 1050 °C. Further, in accordance with invention the sum C+N is limited to $0,20 < C+N < 0,34$ and the sum Mn+Ni is limited to $4,0 < Mn+Ni < 8,5$. In FIG 3 the possible constraints of the SFE are also added. The chemical composition window, which lies within the frame of the area p', q' r' and s' in Fig. 3, is defined with the following labelled positions of the coordination in the table 5.

Table 5

	Si+Cr %	Cu+Mo+0,5W %	C+N %	Mn+Ni %
P'	17,6	3,5	0,34	4,0
q'	16,2	5,7	0,34	8,5
r'	19,0	1,8	0,20	8,5
s'	19,0	1,8	0,20	4,0

[0050] The effect of the limitations for C+N and Mn+Ni with the preferred ranges for the element contents of the invention is that the chemical composition window of Fig. 3 is limited solely by the limitations for the minimum and maximum sums of C+N and Mn+Ni when the sums of Si+Cr and Cu+Mo+0,5W are any value within in the preferred range of the invention. This is because none of the limiting constraints of M_{d30} , PRE or SFE are within the composition limits of the sums of Si+Cr and Cu+Mo+0,5W

[0051] Fig. 4 illustrates one chemical composition example window of Fig. 3 with the constant values of 17,6 for Cr+Si and 3,5 for Cu+Mo+0.5W and further, with the limitations of $0,20 < C+N < 0,34$ and $4,0 < Mn+Ni$. The chemical composition window, which lies within the frame of the area p, q, r and s in Fig. 4, is defined with the following labelled positions of the coordination in the table 6.

Table 6

	Si+Cr %	Cu+Mo+0,5W %	C+N %	Mn+Ni %
P	17,6	3,5	0,34	4,0
q	17,6	3,5	0,34	7,6
r	17,6	3,5	0,20	8,2
s	17,6	3,5	0,20	4,4

[0052] Fig 4 shows that that the composition ranges of the invention for the sums of C+N and Mn+Ni are now limited by the constraint of the calculated $M_{d30} > -30$ (alternatively Nohara $M_{d30} < -70$) and SFE > 10 when the composition limits for Si+Cr and Cu+Mo+0.5W have the constant values as given in Table 6.

[0053] The austenitic ferritic austenitic stainless steel of the invention can be produced as ingots, slabs, blooms, billets and flat products such as plates, sheets, strips, coils, and long products such as bars, rods, wires, profiles and shapes,

seamless and welded tubes and/or pipes. Further, additional products such as metallic powder, formed shapes and profiles can be produced.

5 Claims

1. Austenitic stainless steel utilizing the TRIP effect with a balanced pitting resistance equivalent for high corrosion resistance **characterized in that** the austenitic stainless steel contains 0-0.04 weight % C, 0.2-0.8 weight % Si, 0-2.0 weight % Mn, 16.0-19.0 weight % Cr, 4.0-6.5 weight % Ni, 1.0-4.0 weight % Mo, 0-4.0 weight % W, 0-2.0 weight % Cu, 0.20-0.30 weight % N, the rest being iron and inevitable impurities occurring in stainless steels, the proportion of the ferrite phase in the microstructure is 0-10.0 volume %, the rest being austenite, when quenched and heat treated at the temperature range of 900 - 1200°C, preferably 950 - 1150 °C.
2. Austenitic stainless steel according to the claim 1, **characterized in that** the pitting resistance equivalent value (PRE) is in the range of 27-35.
3. Austenitic stainless steel according to the claim 1 or 2, **characterized in that** the calculated M_{d30} temperature is in the range of -70 to +60 °C, preferably in the range of -30 to +60 °C.
4. Austenitic stainless steel according to any of the preceding claims, **characterized in that** the calculated SFE is in the range of 10.0-16.0mJ/m².
5. Austenitic stainless steel according to any of the preceding claims, **characterized in that** the critical pitting temperature CPT is 30-50°C.
6. Austenitic stainless steel according to any of the preceding claims, **characterized in that** the chromium content is 16.5-18.7 weight %.
7. Austenitic stainless steel according to any of the preceding claims, **characterized in that** the nickel content is 4.5-6.2 weight %.
8. Austenitic stainless steel according to any of the preceding claims, **characterized in that** the manganese content is 0-1.5 weight %.
9. Austenitic stainless steel according to any of the preceding claims, **characterized in that** the copper content is less than 0-1.5 weight %.
10. Austenitic stainless steel according to any of the preceding claims, **characterized in that** the tungsten content is 1.0-3.8 weight %.
11. Austenitic stainless steel according to any of the preceding claims, **characterized in that** the sum of the molybdenum (Mo) and tungsten (W) contents according to the formula (Mo + 0.5W) is in the range 0-4.0 weight %, preferably 2.2 - 4.0 weight %.
12. Austenitic stainless steel according to any of the preceding claims, **characterized in that** nitrogen content is 0.21 - 0.29 weight %.
13. Austenitic stainless steel according to any of the preceding claims, **characterized in that** the stainless steel further contains one or more added elements selected from the group consisting of 0.0001 - 0.04 weight % Al, preferably 0.0001 - 0.03 weight % Al, 0.0001 - 0.004 weight % B, 0.0001 - 0.004 weight % Ca, 0.0001 - 0.1 weight % Ce, 0.0001 - 0.1 weight % Co, 0.0001 - 0.1 weight % Nb, 0.0001 - 0.1 weight % Ti, 0.0001 - 0.2 weight % V.
14. Austenitic stainless steel according to any of the preceding claims, **characterized in that** the stainless steel contains as inevitable impurities 0.0001-0.010 weight %, preferably 0.0001-0.005 weight % S, 0.0001-0.040 weight % P so that the sum (S+P) is 0.0001-0.04 weight %, and the total oxygen content is in the range 0-100 ppm.
15. Austenitic stainless steel according to the claim 1, **characterized in that** the chemical composition window, which lies within the frame of the area a', b', c', d', e', f' and g' in Fig. 1, is defined with the following labelled positions of

the coordination in weight %.

	Si+Cr %	Cu+Mo+0,5W %	C+N %	Mn+Ni %
a'	19,8	1,0	0,24	8,5
b'	19,8	4,4	0,21	4,0
c'	18,8	5,6	0,21	4,0
d'	17,4	6,0	0,21	5,5
e'	16,2	6,0	0,30	4,0
f'	16,2	2,1	0,33	6,2
g	19,6	1,0	0,28	6,2

16. Austenitic stainless steel according to the claim 1, **characterized in that** the chemical composition window, which lies within the frame of the area p', q' r' and s' in Fig. 3, is defined with the following labelled positions of the coordination in weight %.

	Si+Cr %	Cu+Mo+0,5W %	C+N %	Mn+Ni %
P'	17,6	3,5	0,34	4,0
q'	16,2	5,7	0,34	8,5
r'	19,0	1,8	0,20	8,5
s'	19,0	1,8	0,20	4,0

17. Austenitic stainless steel according to the claim 1, **characterized in that** the steel is produced as ingots, slabs, blooms, billets, plates, sheets, strips, coils, bars, rods, wires, profiles and shapes, seamless and welded tubes and/or pipes, metallic powder, formed shapes and profiles.

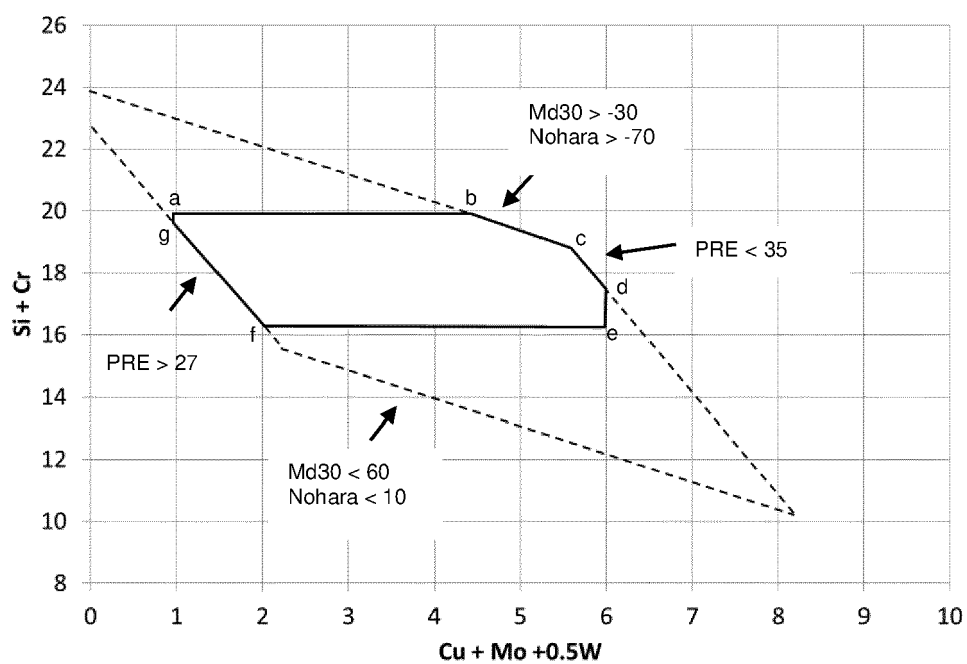


Fig. 1

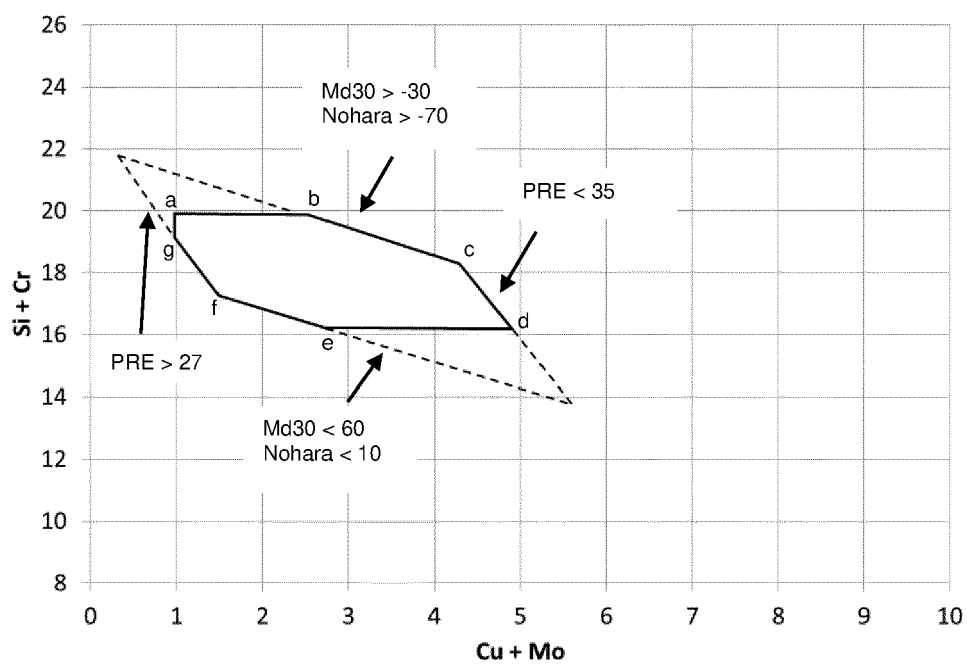


Fig. 2

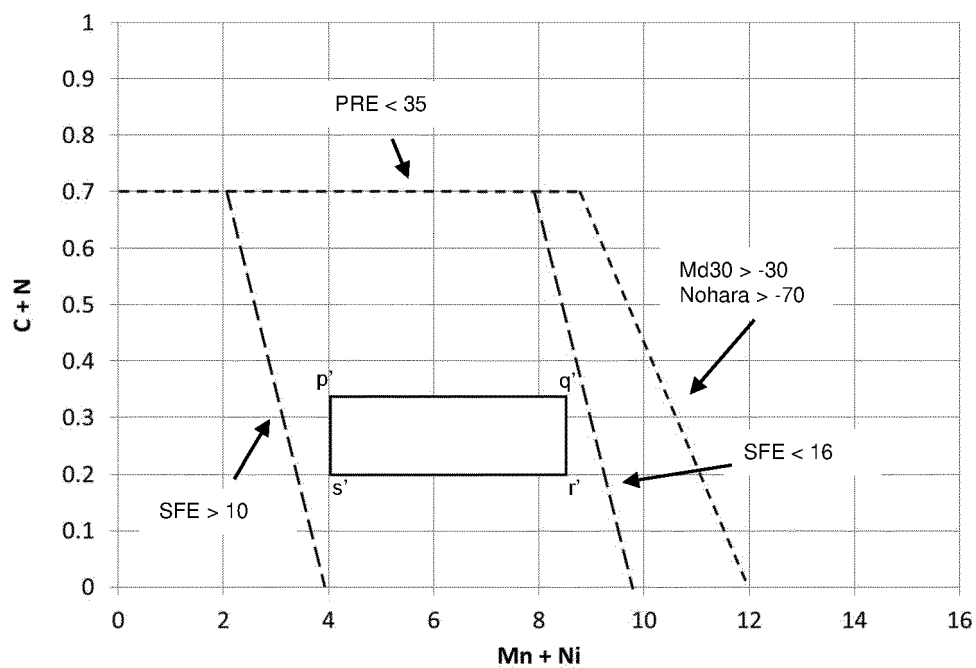


Fig. 3

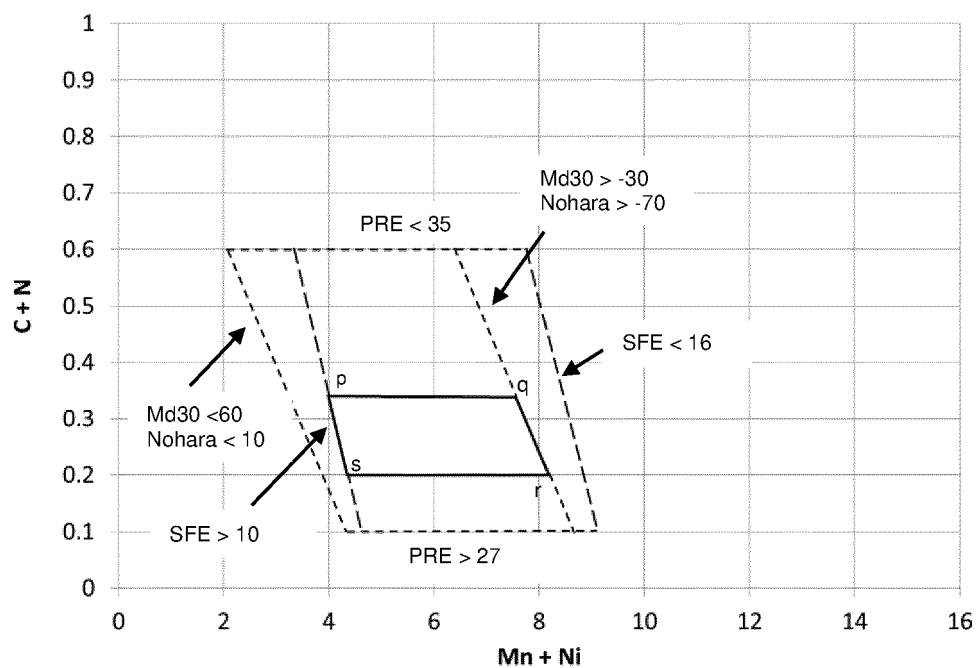


Fig. 4

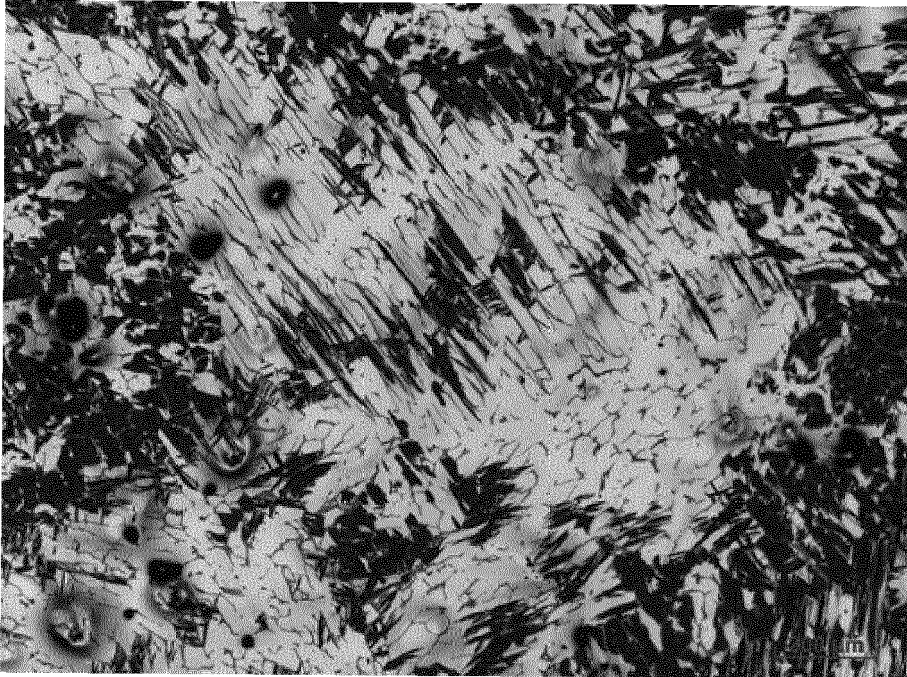


FIG. 5

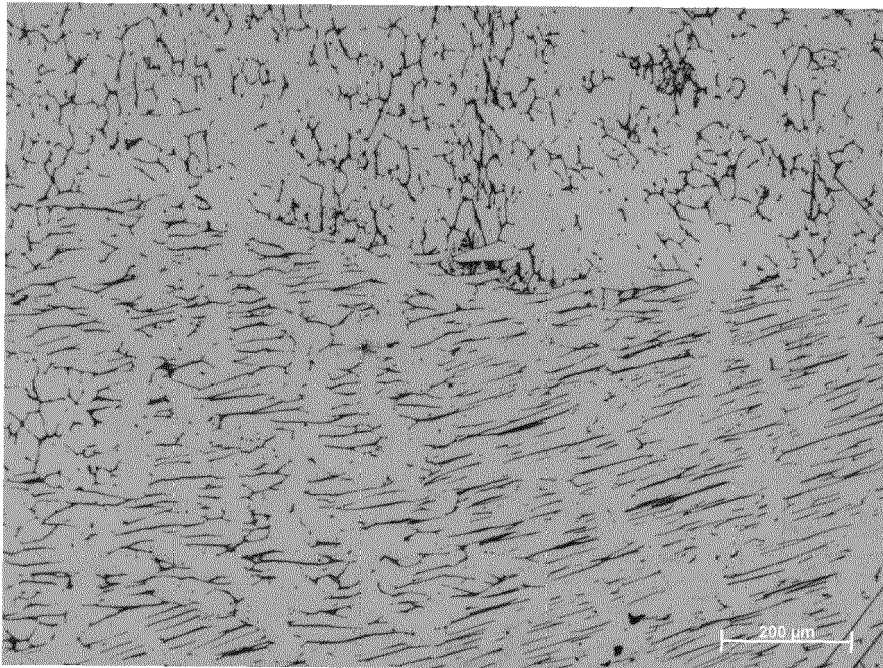


FIG 6.

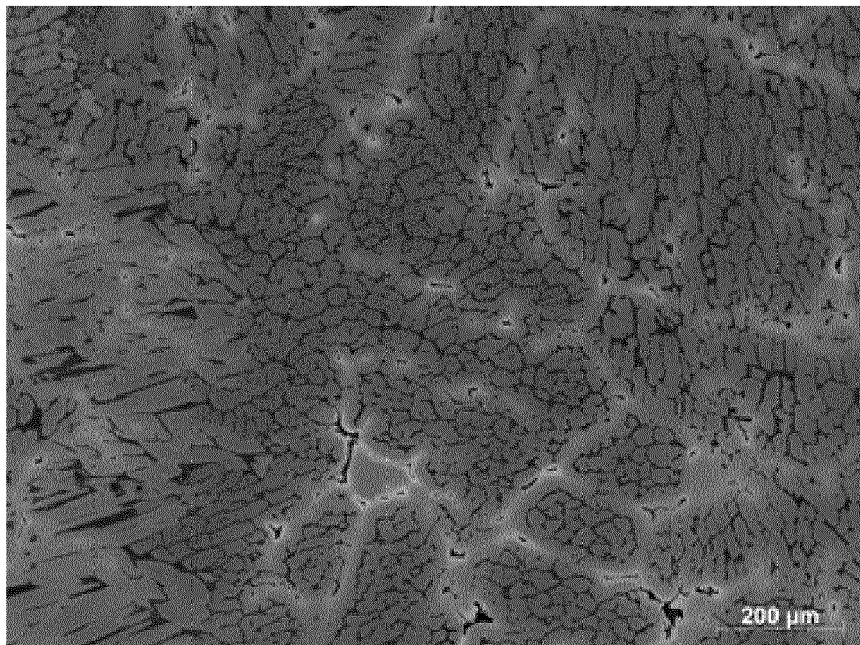


FIG. 7



EUROPEAN SEARCH REPORT

 Application Number
EP 20 19 3794

5

10

15

20

25

30

35

40

45

50

55

DOCUMENTS CONSIDERED TO BE RELEVANT			
Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (IPC)
X	EP 2 832 886 A1 (NIPPON STEEL & SUMIKIN SST [JP]) 4 February 2015 (2015-02-04)	1-14,17	INV. C21D6/00
A	* abstract * * claims 1-3 *	15,16	C22C38/00 C22C38/44 C22C38/02 C22C38/04
X	US 4 960 470 A (HONKURA YOSHINOBU [JP] ET AL) 2 October 1990 (1990-10-02)	1-14,17	ADD. C22C38/42
A	* abstract * * claims 1-2 * * paragraph [0034] *	15,16	C22C38/46 C22C38/58 C21D9/46
X,D	JP 2014 001422 A (NIPPON STEEL & SUMITOMO METAL CORP) 9 January 2014 (2014-01-09)	1-14,17	
A	* abstract * * claims 1-3 * * paragraph [0024] * * table 1 *	15,16	
A	EP 3 158 101 A1 (OUTOKUMPU OY [FI]) 26 April 2017 (2017-04-26)	1-17	TECHNICAL FIELDS SEARCHED (IPC)
	* abstract * * claim 1 *		C21D C22C
A	JP H08 104921 A (NIPPON STEEL CORP) 23 April 1996 (1996-04-23)	1-17	
	* abstract * * claims 1-2 *		
A	EP 0 659 896 A1 (SHINKO WIRE CO LTD [JP]) 28 June 1995 (1995-06-28)	1-17	
	* abstract * * claims 1,6 *		
A	WO 2015/063374 A1 (OUTOKUMPU OY [FI]) 7 May 2015 (2015-05-07)	1-17	
	* abstract * * claims 1-6,12 *		
		-/--	
The present search report has been drawn up for all claims			
Place of search The Hague		Date of completion of the search 19 October 2020	Examiner Vermeulen, Yves
CATEGORY OF CITED DOCUMENTS X : particularly relevant if taken alone Y : particularly relevant if combined with another document of the same category A : technological background O : non-written disclosure P : intermediate document T : theory or principle underlying the invention E : earlier patent document, but published on, or after the filing date D : document cited in the application L : document cited for other reasons & : member of the same patent family, corresponding document			



EUROPEAN SEARCH REPORT

Application Number
EP 20 19 3794

5

10

15

20

25

30

35

40

45

50

55

DOCUMENTS CONSIDERED TO BE RELEVANT			
Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (IPC)
A	WO 2015/087376 A1 (NIPPON STEEL & SUMITOMO METAL CORP [JP]) 18 June 2015 (2015-06-18) * claims 1-4 * -----	1-17	
			TECHNICAL FIELDS SEARCHED (IPC)
The present search report has been drawn up for all claims			
Place of search The Hague		Date of completion of the search 19 October 2020	Examiner Vermeulen, Yves
CATEGORY OF CITED DOCUMENTS			
X : particularly relevant if taken alone Y : particularly relevant if combined with another document of the same category A : technological background O : non-written disclosure P : intermediate document		T : theory or principle underlying the invention E : earlier patent document, but published on, or after the filing date D : document cited in the application L : document cited for other reasons & : member of the same patent family, corresponding document	

1
EPO FORM 1503 03.82 (P04C01)

ANNEX TO THE EUROPEAN SEARCH REPORT
ON EUROPEAN PATENT APPLICATION NO.

EP 20 19 3794

5

This annex lists the patent family members relating to the patent documents cited in the above-mentioned European search report. The members are as contained in the European Patent Office EDP file on
The European Patent Office is in no way liable for these particulars which are merely given for the purpose of information.

19-10-2020

10

15

20

25

30

35

40

45

50

55

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
EP 2832886 A1	04-02-2015	CN 104169450 A	26-11-2014
		EP 2832886 A1	04-02-2015
		HU E048418 T2	28-07-2020
		JP 5794945 B2	14-10-2015
		JP 2013209730 A	10-10-2013
		KR 20140129261 A	06-11-2014
		PL 2832886 T3	29-06-2020
		US 2015083283 A1	26-03-2015
		WO 2013147027 A1	03-10-2013

US 4960470 A	02-10-1990	JP H0445576 B2	27-07-1992
		JP S60208459 A	21-10-1985
		US 4960470 A	02-10-1990
		US 4975131 A	04-12-1990

JP 2014001422 A	09-01-2014	NONE	

EP 3158101 A1	26-04-2017	AU 2015275997 A1	05-01-2017
		BR 112016029428 A2	22-08-2017
		CA 2951867 A1	23-12-2015
		CN 106661704 A	10-05-2017
		EA 201692322 A1	30-06-2017
		EP 3158101 A1	26-04-2017
		ES 2719758 T3	12-07-2019
		FI 126577 B	28-02-2017
		JP 6388967 B2	12-09-2018
		JP 2017522453 A	10-08-2017
		KR 20170016487 A	13-02-2017
		KR 20190030777 A	22-03-2019
		SI 3158101 T1	31-05-2019
		TR 201906644 T4	21-05-2019
		TW 201608040 A	01-03-2016
		US 2017130305 A1	11-05-2017
		WO 2015193542 A1	23-12-2015
		ZA 201608742 B	29-05-2019

JP H08104921 A	23-04-1996	NONE	

EP 0659896 A1	28-06-1995	AU 664336 B2	09-11-1995
		CA 2125540 A1	21-06-1995
		DE 69402814 T2	18-09-1997
		EP 0659896 A1	28-06-1995
		ES 2100595 T3	16-06-1997
		JP 2783504 B2	06-08-1998
		JP H07173579 A	11-07-1995
		KR 950018538 A	22-07-1995

EPO FORM P0459

For more details about this annex : see Official Journal of the European Patent Office, No. 12/82

**ANNEX TO THE EUROPEAN SEARCH REPORT
ON EUROPEAN PATENT APPLICATION NO.**

EP 20 19 3794

5

This annex lists the patent family members relating to the patent documents cited in the above-mentioned European search report. The members are as contained in the European Patent Office EDP file on
The European Patent Office is in no way liable for these particulars which are merely given for the purpose of information.

19-10-2020

10

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
		TW 299357 B	01-03-1997
		US 5716466 A	10-02-1998

WO 2015063374 A1	07-05-2015	FI 125105 B	15-06-2015
		TW 201522661 A	16-06-2015
		WO 2015063374 A1	07-05-2015

WO 2015087376 A1	18-06-2015	CN 105452505 A	30-03-2016
		JP 6029662 B2	24-11-2016
		JP W02015087376 A1	16-03-2017
		KR 20160018748 A	17-02-2016
		WO 2015087376 A1	18-06-2015

15

20

25

30

35

40

45

50

EPO FORM P0459

55

For more details about this annex : see Official Journal of the European Patent Office, No. 12/82

REFERENCES CITED IN THE DESCRIPTION

This list of references cited by the applicant is for the reader's convenience only. It does not form part of the European patent document. Even though great care has been taken in compiling the references, errors or omissions cannot be excluded and the EPO disclaims all liability in this regard.

Patent documents cited in the description

- WO 2015114222 A [0003] [0004] [0041]
- WO 2011135170 A [0005]
- WO 2013034804 A [0006] [0007]
- JP 2014001422 A [0008]

Non-patent literature cited in the description

- **G. MERIC DE BELLEFON ; J. C. VAN DUYSSEN ; K. SRIDHARAN.** Composition-dependence of stacking fault energy in austenitic stainless steels through linear regression with random intercepts. *J. Nucl. Mater.*, vol. 492 [0043]