KAIVOSTOIMINNAN MATERIAALIT JA MAHDOLLISUUDET

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Synopsis

- The predominant mechanisms in the degradation of materials in mines are wear, corrosion, and fatigue.
- Material usages in various parts of the mining operation - old issues and new challenges ?

A—Mortar. B—Upright posts. C—Cross-beams. D—Stamps. E—Their heads. F—Axle (cam-shaft). G—Tooth of the stamp (tappet). H—Teeth of axle (cams).

Source: The Journal of The South African Institute of Mining and Metallurgy, July/August 1996

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Material selection in the mining industry

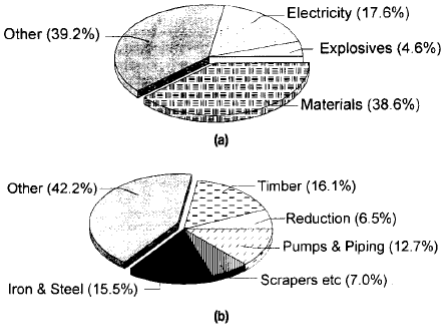
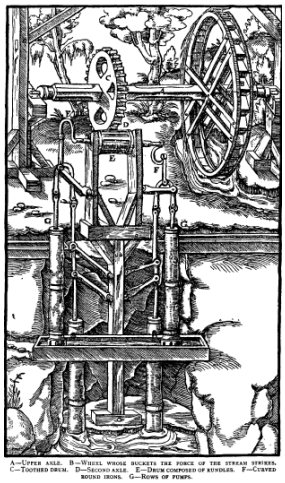


Figure 2—Breakdowns for gold and coal mines affiliated to the Chamber of Mines for 1990
(a) Items consumed
(b) Materials consumed

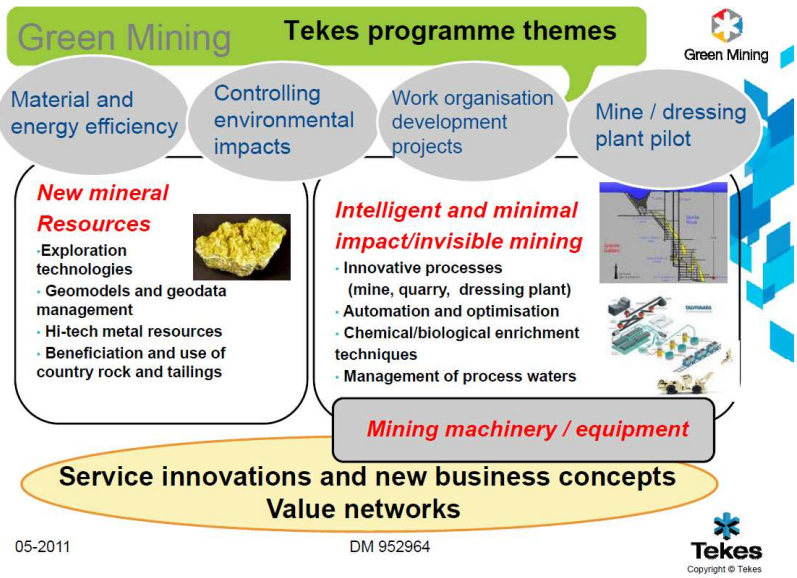
Source: The Journal of The South African Institute of Mining and Metallurgy, July/August 1996



A—Upper axle. B—Wheel whose buckets take force of the stream stirrer. C—Toothed drum. D—Second axle. E—Drum composed of rundles. F—Curved round irons. G—Rows of pumps.

Selection of materials for mining equipment

Application	Environment	Materials
Crushing and grinding	Heavy pressure, shock-impact loading	Austenitic manganese steels (ASTM A128), 4300 series, ASTM A579 alloy steel, 8600 series
Mill liners, grates, and abrasion-resistant plates	Severe gouging, crushing impact and wear, wet (pH 5–8)	Austenitic manganese steels, martensitic chromium-molybdenum white cast iron, martensitic high-chromium white cast iron, martensitic nickel–chromium white iron, martensitic medium-carbon chromium-molybdenum steel, austenitic 6Mn-1Mo steel, pearlitic high-carbon steel, pearlitic white cast iron
Grinding balls (Ref 11, 12)	Severe gouging, crushing impact and wear, wet (pH 6–8)	Pearlitic white cast iron, martensitic white cast iron, forged (0.8% C) steel, 4155, Ni-hard type 1, Ni-hard type 4
Grinding rods (Ref 11, 12)	Severe gouging, crushing impact and wear, wet (pH 6–8)	Heat treated alloy steel, 52100 (UNS G52986), hot-rolled AISI 1095 modified with 1.2% Mn, hot-rolled 1095 with 0.4% Mn
Gearing for mining machinery	Wet, lubricated (pH 5–8) wear, light duty	Carburized 1015, 1020, 1022, 1117, 1118, heat treated 4340, 8645
	Wet, lubricated (pH 5–8) wear, moderate duty	Carburized 8628, 4620, 4615, or equivalent
	Wet, lubricated (pH 5–8) wear, heavy duty	Carburized 4820, 4320, 2320, or equivalent; nitrided 4340, 4140, 4350, and 2.5% Cr steel
Load-haul-dump equipment	Wet (pH 5–8) wear, impact	1020, cast carbon steel, cast austenitic manganese steels (ASTM A128), cast ASTM A 579 steel, ASTM A514 steel
Percussion drilling tools	Wear, impact, gouging (pH 6–8)	Carburized 4320, 8620, and 9315; quenched-and-tempered 4140
Hardfacing	High-impact, wet (pH 6–8)	Austenitic manganese steels
	Unlubricated metal-to-metal rolling or sliding	Self-hardened, air-hardened steels
	Highly abrasive conditions, wet (pH 6–8)	High-carbon high-chromium white cast iron, high-chromium white cast iron
	Sliding abrasion on cutting edge of drilling tools, wet (pH 6–8)	Special tungsten- and boron-containing weld deposits
	Abrasion at high temperature and/or corrosion	High-nickel or high-cobalt weld deposits
Pumps	pH (0–13), abradants	Type 304 or 316 stainless steel, Ni-hard types 1 and 4, 27% Cr white cast irons
	pH (0–13), abradants	Low-carbon, high-manganese steels
	pH (0–13), abradants	Low-alloy cast iron
	pH (0–13), abradants	ACI CD-4MCu
	pH (0–13), abradants	ACI CF-3M (low carbon for as-welded corrosion resistance)
	pH (0–13), abradants	ACI CN-7M (niobium or titanium for as-welded corrosion resistance)
	pH (0–13), abradants	ASTM A484 steel (low carbon for as-welded corrosion resistance)
	High-temperature environments	ASTM A743 or A744 nickel-base alloy, grade CZ-100
Flotation cells	Corrosive, pH (0–5)	Ni-hard type 1, type 316 stainless steel
Paddles	Corrosive, pH (0–5)	Fiberglass-reinforced plastic and rubber
Spirals	Abrasive	Ni-hard type 1
Classifiers blades	...	Ni-hard type 4
Ore chutes	Impact, gouging, abrasion, pH 6–8	Ni-hard, nickel-containing manganese steel
Scrapers	Impact loading, gouging, abrasion	Cast ASTM A579 steel, Ni-hard cast iron, hard cast irons
Wire rope	Corrosive-abrasive, pH 2–12	Kevlar (E.I. DuPont de Nemours and Co., Wilmington, DE), steel wire rope
Piping	Corrosive-abrasive	Type 316 stainless steel, CN-7M, Ni-hard cast irons, rubber covered fiberglass-reinforced plastic
Scrubbers	Off-gas products	High-grade nickel alloys
Chain conveyors	Corrosive-abrasive	Plated (nickel, cadmium, or zinc) steels



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Stainless steels

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May 13, 2013

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The 'family tree' of stainless steels

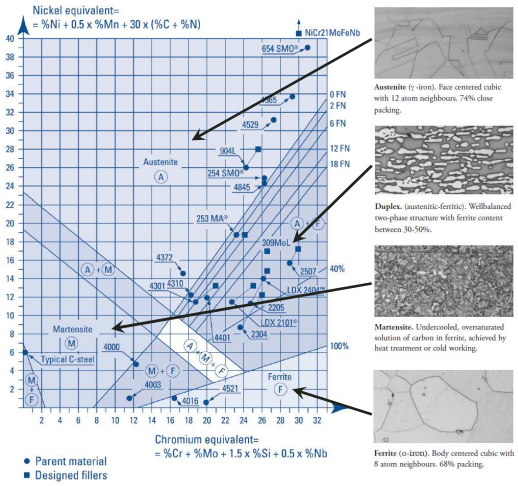
- Martensitic stainless steels:
  - 12-14% Cr and > 0.1% C (also low-carbon qualities available)
  - Corrosion resistance like 12-% chromium ferritic steels
  - E.g. for knifes and chirurgic tools
- Ferritic stainless steels:
  - At least 10.5% Cr
  - 12% Cr, e.g. for exhaust pipes and building & construction
  - 17% Cr, e.g. for kitchen machines
  - 'Superferritic' stainless steels (> 20% Cr and Mo), e.g. for high temperature applications

The 'family tree' of stainless steels

- Austenitic stainless steels:
  - 17% Cr / 7% Ni - meta-stable stainless steel
  - 18% Cr / 8% Ni - 'ordinary' stainless steel
  - 18% Cr / 10% Ni / 2% Mo - 'acid proof' stainless steel
  - High-alloyed stainless steels
  - For general applications
- Duplex stainless steels:
  - > 20% Cr, < 7% Ni, 3-6%, Mo and ~0.2% N
  - Austenite and ferrite in the steel: about 50:50
  - E.g. for pulp & paper, process industry and off-shore applications

Schaeffler Diagram and Microstructures

- The Schaefller diagram, here a version modified by Outokumpu, is traditionally used to predict delta ferrite content in weld metal from chemical composition.
- It may also be used to characterise stainless steel microstructures (ferritic, martensitic, austenitic) and to compare the structural balance in similar grades or casts with the same processing history.



Important stainless steel grades

Family	EN	UNS	ASTM	C	Mn	Cr	Ni	Mo
Ferritic grades	1.4003	S40977	-	0.01	1.4	11.2	0.4	
	1.4512	S40900	409	0.01		11.5		
	1.4016	S43000	430	0.05		16.2		
	1.4510	S43035	439	0.02		17.3		
	1.4509	S43940	441	0.02		18.0		
	1.4521	S44400	444	0.02		18.0		2.0
Austenitic grades without Mo	1.4372	S20100	201	0.07	6.8	17.2	4.1	0.2
	1.4310	S30100	301	~ 0.10		~ 16.7	~ 6.7	~ 0.5
	1.4318	S30153	301LN	0.02		17.5	6.5	
	1.4301	**S30400**	**304**	0.05		18.2	8.1	
	1.4307	**S30403**	**304L**	0.02		18.2	8.1	
	1.4541	S32100	321	0.04		17.2	9.1	
Austenitic grades with Mo	**1.4401**	**S31600**	**316**	0.04		17.1	10.6	2.0
	1.4404	**S31603**	**316L**	0.02		17.0	10.1	2.0
	1.4432	S31603	316L	0.02		16.8	10.6	2.5
	1.4571	S31635	316Ti	0.04		16.7	10.6	2.0
	1.4539	N08904	904L	0.01		20.0	25.0	4.3
	1.4547	S31254	254SMO	0.01		20.0	18.0	6.1
Duplex grades	1.4162	S32101	LDX2101	0.03	5.0	21.5	1.6	0.3
	1.4362	S32304	2304	0.02		23.3	4.8	0.5
	1.4462	S32205	2205	0.02		22.4	5.7	3.2

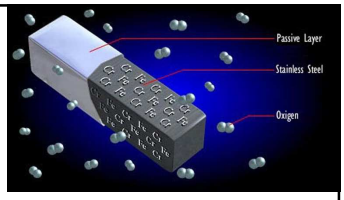
Product properties of stainless steels

Material selection

There are many different grades of stainless steel. As with any other material choice, selecting the correct grades is a balance between many factors and requirements:

- Corrosion resistance
- Operating temperature
- Mechanical strength – influences thickness and weight
- Other mechanical properties (impact toughness, creep resistance, ...)
- Fabrication and welding
- Surface aspects (cleanability, appearance,...)
- Physical properties
- Availability, confidence in suppliers
- Cost, Life Cycle Cost (LCC), Tooling cost
- Recyclability, environmental impacts and benefits
- Legislation, Standards and Approvals
- Degree of comfort, (risks, insurance)

The Passive Layer



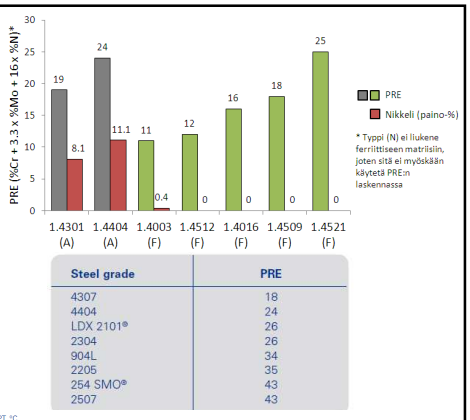
Source: Acesita

- Properties:
  - Tight and corrosion resistant
  - Contains much chromium (and molybdenum *).
  - Only 5-15 nm thick
  - Electrically conductive and usually invisible
- Growth of the passive layer:
  - It grows by itself in air (1 to 3 days) and in oxygen containing water.
  - It grows anew by itself after the stainless surface had been damaged.
  - It becomes stronger with the help of a passivation agent.

* If the steel grade is molybdenum-alloyed.

Corrosion resistance

- The resistance to pitting and crevice corrosion increases with the content of chromium, molybdenum and nitrogen in the steel. This is often illustrated by the pitting resistance equivalent (PRE) for the material, which can be calculated by using the formula:
  PRE = %Cr + 3,3x%Mo + 16x%N.
- The PRE value can be used for a rough comparison between different materials.
- A much more reliable way of ranking steels is according to the critical pitting temperature (CPT).



Steel grade	PRE
4307	18
4404	24
LDX 2101®	26
2304	26
904L	34
2205	35
254 SMO®	43
2507	43

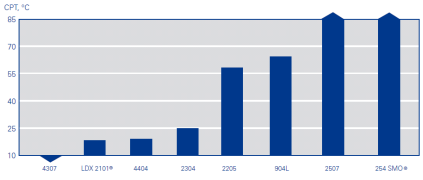


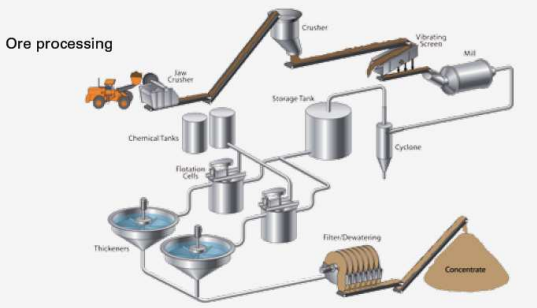
Fig. 5. Typical critical pitting corrosion temperatures (CPT) in 1M NaCl measured according to ASTM G150 using the Avesta Cell. Test surfaces wet ground to 320 mesh. CPT varies with product form and surface finish.

Corrosion in the mining industry

- Corrosion in the mining industry can be characterized as chemical attack enhanced by wear

  synergy effect: corrosion accelerates wear and wear accelerates corrosion

- Mine atmospheres and mine waters vary widely from mine to mine
  - Temperature
  - Humidity
  - pH
  - Chlorine content
  - Sulfate ion content
  - Dissolved colloidal consituents and suspended solids
  - Microbiological organisms



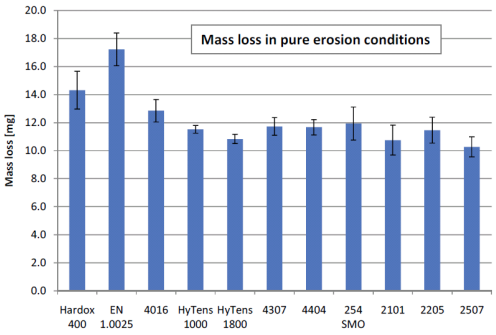
Strength Classes acc. to EN 1993-1-4: 2006

Strength level	Steel grade	$R_{p0,2}$ Proof strength[1)] [N/mm²] min.	R_m Tensile strength[1)] [N/mm²] min.	Elongation A min. [%]
2B	1.4003	280	450	20
(S235)	1.4301	230	490	45
	1.4401, 1.4571	240	530	40
2B	1.4318	350	650	40
2H+CP350	1.4301, 1.4401	350	700	25
(S355)	1.4571			
2B	1.4462	480	660	20
2H+CP500	1.4318, 1.4301	530	850	20
(S460)	1.4401			

[1] Cold rolled strip, t ≤6 mm

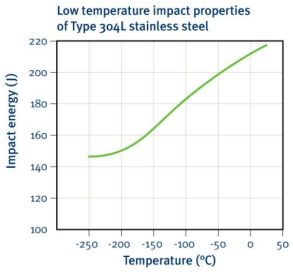
Abrasion wear and stainless steel

- Tallinn University of Technology has, on behalf of Avesta Research Center, performed some abrasion testing, according to ASTM G-65, on different stainless steels and with two carbon steels, Hardox 450 and EN 1.0025, as references.
- The results are seen in Figure.
- The testing has been performed in a dry environment due to the difficulties in maintaining similar testing conditions associated with wet testing.
- The scattering is low, thus giving statistically significant results.
- A more relevant measure would perhaps be volumetric material loss, however, the general trend is the same.



Stainless steel for cryogenic service

- Standard austenitic stainless steels are well suited for equipment handling liquid gases and for other liquids operating at sub-zero temperatures where corrosion resistance is also required.
- As the temperature is lowered the strength of these steels increase rapidly, whilst ductility and impact toughness are maintained at a high level as temperature approaches absolut zero.

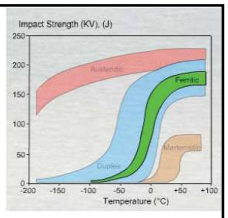


Mechanical Properties, Low Temperatures

Outokumpu steel name	EN No.	EN min. values, MPa and %											
		–196°C				–80°C				RT			
		$R_{p0.2}$	$R_{p1.0}$	R_m	A_5	$R_{p0.2}$	$R_{p1.0}$	R_m	A_5	$R_{p0.2}$	$R_{p1.0}$	R_m	A_5
4307	1.4307	300	400	1200	30	220	290	830	35	200	240	500	45
4301	1.4301	300	400	1250	30	270	350	860	35	210	250	520	45
4311	1.4311	550	650	1250	35	350	420	850	40	270	310	550	40
4541	1.4541	200	240	1200	30	200	240	855	35	200	240	500	40
4404	1.4404	350	450	1200	35	275	355	840	40	220	260	520	45
4406	1.4406	600	700	1150	30	380	450	800	35	280	320	580	40
4429	1.4429	600	700	1150	30	380	450	800	30	280	320	580	35

From EN 10028-7 Annex F.

Ferritic and Duplex grades at low temperatures



- Ferritics have minor impact toughness values at low temperatures because of their high notch sensitivity.
- Structural ferritic stainless steel 1.4003 have superior impact toughness compared to medium and high chromium ferritics.
- Duplex grades can be used down to temperature ca. – 40 °C.

Impact toughness.
Minimum values according to EN 10028, transverse direction, J Table 3

	LDX 2101®*	2304	2205	2507
20°C	60	60	60	60
-40°C	27	40	40	40

* Values from internal standard, AM 611

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Austenitic and Duplex grades at elevated temperature

- Due to the risk of embrittlement, the duplex steels should not be used at temperatures above 250-325℃.

Tensile properties at elevated temperatures.
Minimum values according to EN 10028, MPa Table 4

	LDX 2101®*		2304		2205		2507	
	$R_{p0.2}$	R_m	$R_{p0.2}$	R_m	$R_{p0.2}$	R_m	$R_{p0.2}$	R_m
100°C	380	590	330	540	360	590	450	680
150°C	350	560	300	520	335	570	420	660
200°C	330	540	280	500	315	550	400	640
250°C	320	540	265	490	300	540	380	630

* Values for hot rolled and cold rolled strip according to AM 611

Tensile properties at elevated temperatures.
Proof strength $R_{p0.2}$, MPa, minimum values Table 4a

Steel grade	Temperature, °C				
	100	200	300	400	500
4318	265	185	170	–	–
4307	147	118	100	89	81
4301	157	127	110	98	92
4311	205	157	136	125	119
4541	176	157	136	125	119
4306	147	118	100	89	81

Tensile properties at elevated temperatures.
Proof strength R_m, MPa, minimum values Table 4c

Steel grade	Temperature, °C				
	100	200	300	400	500
4404	530	460	440	–	–
4307	410	360	340	–	–
4301	450	400	380	380	360
4311	490	430	410	–	–
4541	440	390	375	375	360
4306	410	360	340	–	–

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High Temperature Stainless Steels

Characteristic temperatures — **High Temperature Austenitic Stainless Steel** — Table 2

Steel grade	Solidification range, °C	Maximum service temperature in dry air, °C	Hot forming, °C	Solution annealing, °C	Stress relief annealing (min. 0.5 h), °C
4948	1450 - 1385	800	1150 - 850	1050 - 1110	840 - 900
4878	1440 - 1370	800	1150 - 850	1020 - 1120	840 - 900
153 MA™	1450 - 1370	1000	1150 - 900	1020 - 1120	900
4833	1420 - 1350	1000	1150 - 950	1050 - 1150	1010 - 1040
4828	1420 - 1350	1000	1150 - 950	1050 - 1150	1010 - 1040
253 MA®	1430 - 1350	1100	1150 - 900	1020 - 1120	900
4845	1410 - 1340	1100	1150 - 980	1050 - 1150	1040 - 1070
4841	1400 - 1330	1125	1150 - 980	1050 - 1150	1040 - 1070
353 MA®	1410 - 1360	1150	1150 - 980	1100 - 1150	1010 - 1040

Characteristic temperatures — **High Temperature Ferritic Stainless Steel** — Table 2

Steel grade	Maximum service temperature in dry air, °C	Hot forming[1], °C	annealing[2], °C
4713	800	1100-750	750-800
4724	850	1100-750	800-850
4742	1000	1100-750	800-850
4762	1150	1100-750	800-850

[1] cooling still air. [2] cooling forced air or water.

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More information

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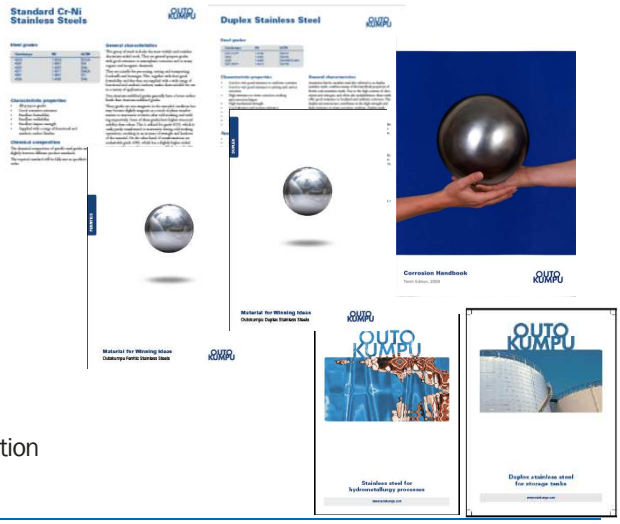
Outokumpu aids for material selection

- Data sheets and brochures
- Corrosion Handbook
- Welding handbook
- Segment and application brochures



Public information for Material Selection

- Euroinox www.euro-inox.org
  - brochures and other publications in local languages
  - links to member associations
- Nickel Institute (NiDi) http://www.nickelinstitute.org
- ISSF www.worldstainless.org
- Finnish Constructional Steelwork Association http://www.terasrakenneyhdistys.fi

Webpages contain useful information, often as downloads

Concluding remarks

- For most applications, there are several suitable stainless steel grades
- Different groups of stainless steel have different properties
- To work out together with the customer the most appropriate solution, we need to understand the application
- Outokumpu provides good aids for material selection
- R&D can support with more detailed information

Applications of stainless steels