STAINLESS STEEL'S SUSTAINABLE ADVANTAGE IN ARCHITECTURE

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Abstract

In the US alone, construction is about a $1.2 trillion market and the segments most familiar to the stainless steel industry are small relative to the total market: power (4.2%), water supply/sewage treatment (3.4%) and roadway/bridge (6.6%).[1] Public, private and government buildings are the bulk of the market and architectural metal use has been growing substantially.

The increased use of architectural metals in this huge market for raw materials presents a significant opportunity for stainless steel, particularly with the growth in "green" construction. Appropriate specification and use of architectural metals are important aspects of sustainable design. Lifecycle assessments (LCA) for individual metal families are available but are often not specific to architectural applications; do not consider differences in environmental conditions, service life, and other project-specific variables; and may have no relevance to the "green" building evaluation systems. Given these issues, it is necessary to assess the relative sustainability of stainless steel products using architects' decision-making tools.

The dominant international approach for evaluating the environmental friendliness of buildings was developed by the World Green Building Council's (WGBC) member countries. While specific elements of "green" building scoring systems can vary, the underlying concepts are similar and they are increasingly driving materials selection decisions.

Competitive products have worked aggressively to influence the scoring systems and decision makers in addition to developing product variations to meet emerging market needs. Stainless steel has tremendous potential in the growing market for "green" structures, but industry involvement has been far more limited. The stainless steel industry needs to understand the fundamentals of the scoring systems and the advantages on which they can capitalize, and then work to influence further system evolution. This paper will review existing opportunities, data requirements and the applications where further industry involvement is needed to capitalize on this long-term market opportunity.

Why Build Green?

Concern about the environment and global climate change have stimulated tremendous interest and demand for "green" construction, but shorter term economic factors also contribute to the stronge corporate and government support for this movement. Industry statistics can be helpful in understanding the potential benefits of "green" construction. In the US, buildings account for about 65% of electricity consumption, 36% of energy use, 30% of greenhouse gas emissions, 12% of potable water consumption, 30% of all raw material production and 30% of waste output. [2] This represents a measureable improvement in US statistics. In the developed world, building construction is believed to be responsible for 40% or more of greenhouse gas emissions and other measurements of environmental impact are also believed to be higher. [3]

The potential for significant reductions in imported energy reliance and building operating cost, improved worker health and productivity, and the market opportunities associated with introducing or promoting “environmentally friendly” products are significant short-term financial and strategic motivators. These inducements, along with a high level of public concern about climate change and public demand for greener structues, have encouraged both corporations and federal governments to fund research and take active roles in the development of green building councils.

Building Evaluation Systems

The United Kingdom’s Building Research Environmental Assessment Method (BREEAM) was the world’s first “green” building rating system (1990) closely followed by the US Green Building Council’s (USGBC) Leadership in Environmental and Engineering Design (LEED). Green Building Councils were subsequently formed in other countries and the World Green Building Council (WGBC) was formed in 2002. Australia, India, Canada and Japan have building scoring systems based on this model.

WGBC currently has eleven active member countries, which represent over 50% of global construction activity. In these countries, federal and local governments support “green” construction through civic building and zoning requirements and incentives. For example, there are 12 federal agencies, 27 states, and 72 cities in the US, which require or encourage “green” construction. China, which is forming a GBC, recently adopted green construction policies and standards and has 11 “green” cities and 140 “green” buildings under construction. An additional fifteen countries are at various stages of establishing GBCs. (See Table 1) “Green” buildings are regularly being built in many other countries that have not formally begun this process.

Table 1. World Green Building Council (GBC) Members and Emerging GBCs

Members	Australia, Brazil, Canada, India, Japan, Mexico, New Zealand, Tiawan, United Arab Emirates, United Kingdom, United States
Emerging GBCs	Argentina, Chile, China, Eygpt, Germany, Greece, Guatamela, Hong Kong, Isreal, Korea, Nigeria, Panama, Philippines, Switzerland, Turkey, Vietnam

While there are scoring system-to-system differences, it can be assumed that at least 85% of the score content will be identical. The US LEED scoring system is the most widely used internationally and Table 2 summarizes the elements of that are relevant to stainless steel. [4] There are 69 available points and there are different “green” building classification levels: certified, 26-32 points; silver, 33-38 points; gold, 39-51 points, and platinum, 52-69 points.

Construction material suppliers have actively influenced the system and extra points can be gained by using “certified” wood; low-VOC adhesives, wood, carpet and coating systems; rapidly renewable materials (i.e. wood); and painted metal roofing. Logically, materials with no VOC emissions, like stainless steel, should yield more points, but the system only awards points for using low VOC products. Furthermore, unless a building is being renovated and materials reused, there is no point advantage associated with material longevity. It is possible to achieve a higher “green” rating with a painted carbon steel roof than with a bare stainless steel roof with a much longer service life.

“Green” architects often understand the inherent problems. Stainless steel is most frequently used when a minimum building design life is required or when a design firm makes a policy decision to take a more environmentally practical approach to design and material specification. In either case, they still have to provide clients with “green” buildings using the existing system. To achieve this balance, they need stainless steel industry support to understand stainless steel’s benefits, help justify specification and influence system change.

The most significant impact of efforts to incorporate life cycle assessments (LCA) into the scoring system has been to require that material surface solar reflectance indexes (SRI) be determined. Starting in mid-2007, the US LEED system began requiring that any new construction project earn at least 2 points for energy reduction (14% decrease) to be considered for certification. Smaller office buildings must earn a minimum of 4 points (21% reduction). The Australian scoring system has also adopted stringent requirements. Eleven of the 69 points in the US LEED systems are associated with optimizing building energy performance.

Table 2. Summary of the US LEED scoring system categories relevant to stainless steel products

Category	Points	Opportunity
Sustainable Sites		
Storm water design: quality control	1	Reduce pollutant loadings in roof run-off
Heat island effect: roof	1	May reduce roof temperature (A)
Energy & atmosphere		
Optimize energy performance	1 - 10	May help to reduce building energy requirements (A)
Materials & resources		
Building reuse: maintain 75% surface area walls, floors, roof	1	May be reused during major renovations
Building reuse: maintain 95% surface area walls, floors, roof	1	May be reused during major renovations
Building reuse: maintain 50% interior non-structural	1	Interior surfaces may be reused
Construction waste management: divert 50% from disposal	1	High recapture rate & reuse is possible
Construction waste management: divert 75% from disposal	1	High recapture rate & reuse is possible
Construction waste management: 5% salvaged materials	1	Product reuse is possible
Construction waste management: use 10% salvaged materials	1	High recapture rate & reuse is possible
Recycled content: 10%	1	Provide industry data
Indoor Environmental Quality		
Indoor chemical & pollutant control	1	Grills/grates limit occupant-borne contaminants from entering building
Total possible points	12-21	

(A) SRI values have to be calculated per ASTM 1980. Steep-sloped roofs must have a minimum SRI of 29 and low-sloped roofs must have a minimum SRI of 78.

Energy Reduction

The current scoring systems place a very high emphasis on building energy reduction which means that roofs and, at a secondary level, wall panels can have a significant influence on the score. Two parts of the scoring system address this issue: heat island effect and optimizing energy reduction. The term "heat island" refers to urban air and surface temperatures that are higher than those of nearby rural areas. Cities and suburbs have air temperatures that are up to 5.6°C (10°F) warmer than the surrounding countryside. Cool roof systems with high reflectance and emittance stay up to 39°C (70°F) cooler than traditional materials during peak summer weather and air conditioning costs can be reduced by 20 to 70%. Air pollution (electricity generation) and smog are also reduced. When air temperatures are above 21 C (70 F), smog increases by 3% for every 0.5 C degree temperature increase.

The US government has funded cool roof material research at several national laboratories since the mid-1990’s, and private and public groups have done additional work. The two most important surface properties are high solar reflectance and thermal emittance. Solar reflectance is the percentage of energy reflected away by a surface. Thermal emittance is the percentage of energy a material radiates away after it is absorbed. The Solar Reflectance Index (SRI) is a formula defined by ASTM E 1980 incorporating both solar reflectance and emittance values which compares surface performance to standardized black and white surfaces. The resultant value is expressed as a fraction (0.0 to 1.0) or percentage.

Conventional roof surfaces have low reflectance (0.05 to 0.25) and high thermal emittance (over 80%) and typically attain temperatures of 66 to 88°C (150 to 190°F) at midday during the summer. Bare metal or roofs with metallic surfaces have high solar reflectance (0.5 or higher), emittance levels that range from 20 to 60% (dependant on surface finish) and typically reach temperatures of 60 to 77°C (140 to 170°F). (The reflectance and emittance of bare metals are very sensitive to surface texture and the presence of surface oxides, oil film, etc.) Cool roofs with high reflectance and high emittance only reach 38 to 49°C (100 to 120°F) in the summer sun.

Table 3 provides data from Lawrence Berkeley National Laboratory's Cool Roofing Database. [5] To obtain credit for heat island reduction, roofs must meet minimum SRI values: steep-sloped roofs, 29; and low-sloped roofs, 78. A minimum SRI of 29 is targeted for wall panels. Both wall panels and roofing play an important role in building energy reduction.

Table 3. Solar Reflectance and Thermal Performance of Roofing

Product	Solar Reflectance	Infrared Emittance	Temperature Rise, C (F)	Solar Reflectance Index (SRI) %
Galvanized steel, new bare	0.61	0.04	30 (55F)	46
Aluminum, new bare	0.61	0.25	27 (48F)	56
Metal, proprietary white coating	0.85	0.91	9 (16F)	107
Clay tile, red	0.33	0.9	32 (58F)	36
Concrete tile, red	0.18	0.91	39 (71F)	17
Concrete tile, white	0.73	0.9	12 (21F)	90
Asphalt, generic white	0.25	0.91	36 (64F)	26
Asphalt, generic black	0.05	0.91	46 (82F)	1
Wood shingle, brown stain	0.22	0.90	37 (67F)	22
Wood shingle, proprietary white coating	0.84	0.89	6 (10F)	106

"Cool" roof coatings contain transparent polymeric materials and a white pigment, such as titanium dioxide or zinc oxide, to make them opaque and able to reflect 70 to 80% of the sun's energy. New coatings are able to achieve high SRI ratings without limiting the roof color to white. The highest values are achieved when coatings are applied to a smooth substrate, such as metal, because they mask its low emittance. Coatings may last 20 or more years but some manufacturers suggest reapplication every 10 years to maintain SRI performance. The scoring system does not consider the negative environmental impact of repeated coating application, substrate service life or system replacement frequency.

Stainless steel finishes are not included in public databases or the US Environmental Protection Agency's roofing comparison calculator software. The US and Australian scoring systems make SRI testing necessary for certified "green" buildings and other systems are expected to adopt this requirement. While testing is starting to occur on a project-by-project basis, suppliers and the industry would benefit if stainless steel SRI data were widely available. Finish modifications that produce improved SRI values should be considered. Participation in the industry and government sponsored Cool Roofing Rating Council (CRRC) could be beneficial, because the organization actively promotes "cool" materials. SRI values deteriorate with time and the CRRC is promoting installed finish testing. Surface accumulations are a recognized cause of deterioration while the role of corrosion has been fully explored. Stainless steel may have a long-term advantage.

Other Score Elements

Stainless steel provides several other potential advantages relative to other construction materials that may improve a building's score. This includes low metal roof runoff rates, a long service life that can permit product reuse, and high recycled content and recapture rates. Points are awarded for the quality of roof run-off and the use of captured water for internal applications where non-potable water can be used (e.g. toilets, showers and laundry) and irrigation. There is concern about runoff from copper, zinc and galvanized roofs and non-metallic roofs like asphalt, and water filtration is one option for obtaining a storm water quality control point. Stainless steel's low runoff levels may make filtration unnecessary.

The aluminum and carbon steel industries have carefully crafted marketing messages using industry-wide data to give the impression that these construction materials have consistently high-recycled contents. Decision makers are generally unaware that the aluminum sheet used in construction contains no recycled content and assume very high recycled content levels. This gives stainless steel an advantage, but, without more data, it may be minimized by a shift toward end-of-life recapture rates. End-of-life recapture rates only consider recycling of the metal left at the end of building life or material replacement. While stainless steel still has an advantage, metal loss to corrosion, which could be a particularly significant factor in more corrosive environments, is not considered. (See Table 4 for a comparison of metal products. [6])

Table 4. Recycled Content Versus End Of Life Recapture Rates

Metal	Recycled Content	End Of Life Recapture Rates
Carbon Steel		
Ingetrated mills	25 - 35	70
Mini mills	≥ 95	97
Stainless Steel	60	> 80
Zinc	23	33
Copper		
Electrical wire	0	> 90
Other products	70 - 95	> 90
Aluminum []		
Sheet	0	70
Extrusions	varies	70
Castings	≤ 100	70

Note: Data was obtained from the industry association websites or telephone conversations except as noted.

Building renovation and material reuse in new projects are the only aspects of the scoring system that currently provides credit for long-term material performance. For example, if an existing building is renovated and a high percentage of existing wall or roof panels, structural steel, and concrete floor decks are reused, the building can earn extra points. The surface area of the material that is reused is used to evaluate point eligibility. Reuse of interior surfaces also earns point credit. There are examples of stainless steel interior and exterior panel reuse that can be used to promote the materials' long-term environmental friendliness and encourage specification in new projects by architects who are aware of the current system limitations. The most effective long-term solution for increasing market potential is to lobby for system changes, possibly with enlightened architectures and other industries with long-lasting products.

Project Examples

The David L. Lawrence Convention Center in Pittsburgh, Pennsylvania, USA was designed by Rafael Vonoly Architects to the highest green design standards. When it was completed in 2003, it was the world's first green convention center and the world's largest green building. The building received a Gold US LEED certification. The architects minimized energy requirements for this 139,350 m^2 (1.5 million ft^2) building by using a sweeping Type 304 stainless steel roof, a natural ventilation system, and skylights to reduce lighting requirements. The building has exceeded energy reduction expectations. On average, the design eliminated the need to use artificial heating or cooling in the exhibit hall during 33% of event days. A low reflectivity roof was required to avoid blinding pilots or reflecting light into nearby buildings. Because there are occasional tornadoes in the area, the stainless steel roof was also designed to withstand hurricane-force winds. (See Table 4.)

The architecture firm IKM Inc. was given the task of renovating the lobby and entrance of a 50-year old stainless steel building in Pittsburgh, Pennsylvania USA. The original stainless steel panels were dirty and scratched. The firm had the panels removed, cleaned, refinished, reshaped and reinstalled in the new lobby design. Any panel that could not be reused was recycled. This high level of interior surface reuse made it a very "green" renovation. (See Figure 2.)

Figures 1 and 2: David L. Lawrence Convention Center's roof helped to reduce building energy requirements. (photo credit: Allegheny Technologies) In this Mellon Bank office building, 50 year old stainless steel was cleaned, refinished and reused in the new design. (photo credit: IKM Inc.)

Conclusions

There are many areas where stainless steel provides initial and long-term benefits relative to other materials. Market education efforts by the Nickel Institute and other organizations are increasing architects awareness of stainless steel's inherent practical advantages, but a broader industry effort is needed to capitalize on this significant international market opportunity. The industry must provide the SRI data required by "green" construction scoring systems, but long-term SRI performance and surface finish research should also be considered. By working within the system and partnering with other interested parties, practical environmentally responsible scoring system changes can be made that capitalize on stainless steel's advantages.

References

[1] U.S. Census Bureau, Manufacturing, Mining, and Construction Statistics

[2] US Green Building Council website. Data summarized from various U.S. government agencies including the U.S. Department of Energy and U.S. Geological Service

[3] World Green Building Council website

[4] Version 2.2 LEED for New Construction and Major Renovations, US Green Building Council website

[5] Lawrence Berkeley National Laboratory, Environmental Technologies Division, Cool Roofing Database

[6] C. Houska and S.B. Young, "Comparing the Sustainability of Architectural Metals", The Construction Specifier Magazine, July 2006, pp. 80 - 90.

A NOVEL VIEW ON MATERIAL SELECTION OF STAINLESS STEELS BY OPTIMIZING MATERIAL COSTS AND PRODUCT PROPERTIES

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Abstract

Material selection of stainless steels for both forming processes and structural applications are reviewed by giving a wide perspective to improved price stability and to enhanced product properties compared to the classic and multifunctional CrNi-grade 1.4301 (AISI 304). Demand to find better price stability is the driving force for replacing nickel with elements like manganese, nitrogen, carbon and copper. The mechanical properties, corrosion resistance and some other parameters that have to be taken into account in the material selection process will be reviewed and compared to each other. Additionally, the use of novel thermo-mechanical treatments give new possibilities to benefit more efficiently new and traditional stainless steel grades, even grade 1.4301. Temper rolling, intermediate annealing in multi-phase forming, bake hardening and reversion annealing are to be considered depending on whether higher strength or enhanced forming properties are desired. A schematic illustration combining both the materials composition and the thermo-mechanical treatments is drawn in order to ease the better utilisation of the new possibilities for stainless steel in structural and forming applications.

Introduction

During recent years, the nickel price was relatively stable until May 2006. The price level reached an all time high of over 50 000 USD in June 2007. This has caused users of stainless steel to consider alternative materials even for well-established applications as the high nickel prices led to a significant increase of the alloy surcharges. However, the absolute nickel price in Euro was one third lower than the absolute price in US Dollar, Figure 1. This discrepancy was caused by a relatively weak exchange rate of US Dollar to Euro and enhanced further by higher inflation rates in the USA compared to Europe.

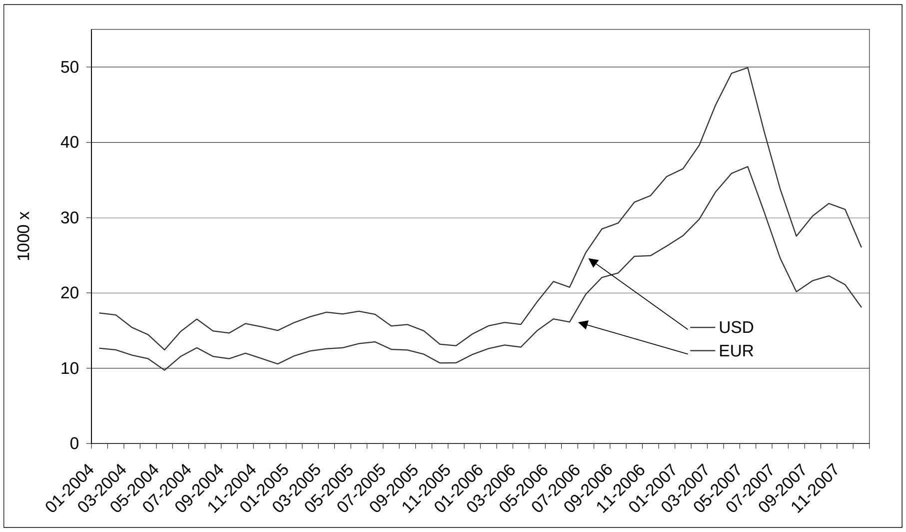

Figure 1. Nickel prices according to the London Metal Exchange (LME, 3-Months Seller) from 2004 to 2007. The applied inflation adjustment is based on the customer price indices (CPI) in the USA and in the EU. Between 2004 and 2007, the US American CPI increased by 14.2 % while the European CPI gained only by 5.1 %. Sources: LME, Bank of Finland and U.S. Department of Labour.

Dramatic changes of raw material prices emerged almost in every second decade and the stainless steel market reacted always by seeking less expensive alternatives. However, changing the steel grade to a material with a cheaper composition can have detrimental consequences and a lack of knowledge of material properties can cause difficulties either in manufacturing or final use of the finished product. In addition, the availability of the chosen alternative has to be considered during the material selection process.

Nowadays, the replacement of the well-established multipurpose CrNi-grade 1.4301 is directed towards new alloys like new leaner duplex grades (e.g. 1.4162) and ferritic grades with increased chromium content (e.g. 1.4509). Also low nickel austenitic grades (e.g. 1.4318) and the re-discovered CrMn-grades (e.g. 1.4372) have been emerging during the recent high raw material price period. Several papers and articles on ferritic grades or the 200-series and even substitution stories were published during the last years emphasising a wide variety of substitution strategies and material alternatives that need to be studied and tested before material replacement. [1-6]

Structural applications

The use of stainless steel in structural applications has been growing steadily and several buildings from the 1990’s ranging from the facades of the Petronas Twin Towers in Kuala Lumpur, Malaysia to the structural elements of the Sanomatalo in Helsinki, Finland are making use of the easy-to-maintain properties and aesthetic value of stainless steel. At the same time, design guidelines for stainless steel were developed. [7-8] Also the transportation industry is increasingly interested in stainless steel as material for structural use besides the traditional automotive exhaust systems. Despite its excellent mechanical properties, material testing and verification took such a long time that the recent high raw material prices caused decision makers reconsider again their recent material selections.

Steel grade selection for structural applications

With the help of a proper material selection process, it is possible to optimise the combination of strength and corrosion resistance that the many different available stainless steel grades offer for structural applications. In Table 1, some stainless steel grades that can be considered as alternative materials to the common grade 1.4307 are listed. All these materials have a lower nickel content compared to grade 1.4307 resulting in less volatile prices. The price level of the lowest alloyed grade 1.4003 is typically about 0.5- to 0.7-times that of the listed austenitic and duplex grades. The carbon content of structural materials should be below 0.03 % when materials with a wall thickness of over 6 mm shall be welded with conventional fusion welding methods. In order to prevent staining and pitting corrosion in outdoor applications, it is advised to select a steel grade having a pitting potential equivalent (PRE) of about 20 of higher. Otherwise, a protective coating has to be applied. Superficial corrosion in coastal, industrial and polluted urban areas can be avoided by using even higher alloyed grades than listed in Table 1.

Table 1. Typical chemical compositions of some stainless steel grades for structural applications. The pitting resistance equivalent (PRE) is calculated according to the formula PRE = Cr(wt-%) + 3.3 x Mo(wt-%) + 16 x N(wt-%). Steel designations according to EN 10088-2:2005, EN 10088-4:2005 and ASTM A240-07.

EN	ASTM	C	Cr	Ni	Mn	N	Fe	Note	PRE
1.4307	304L	0.02	18.2	8.1	1.5	0.05	Bal.	Ni enhances repassivation	19
1.4318	301LN	0.02	17.6	6.5	1.2	0.15	Bal.	Ni enhances repassivation	20
1.4372*	201LN	0.02	16.8	4.5	7.0	0.20	Bal.	Cr level to be kept high enough and S level low.	20
1.4162	S2101	0.02	21.5	1.5	5.0	0.22	Bal.	Duplex structure. Lean side composition.	25
1.4003	S40977	0.02	11.5	0.4	1.3	0.02	Bal.	Low alloyed ferritic grade	12

* Typically produced with a higher carbon content of 0.05 %.

As the numbering system of stainless steels is based on their chemical composition, it is difficult to get an idea of the mechanical properties of each grade only based on their name. Therefore, standardised minimum values for different grades are shown in Table 2. It can be clearly seen that all presented alternatives to grade 1.4307 have higher yield strength and higher tensile strength values although their better price stability is caused by their lower nickel content. Nitrogen alloyed austenitic grades have usually a 1.5-times higher and duplex grades typically a 2-times higher yield strength than grade 1.4307.

Table 2. Minimum values for cold rolled strip (transverse to the rolling direction) according to EN 10088-2:2005, EN 10088-4:2005 and ASTM A240-07.

EN grade	AISI / UNS grade	Rp0,2 N/mm^2		Rm N/mm^2		A %	
		EN	ASTM	EN	ASTM	EN	ASTM
1.4307	304L	220	170	520	485	45	40
1.4318	301LN	350	240	650	550	40	45
1.4372	201LN	350	310	750	655	45	45
1.4162	S32101	530	530	700	700	30	30
1.4003	S40977	320	280	450	450	20	18

The structural use of manganese alloyed stainless steels may be restricted for pressurised applications because of their absence in EN 10028-7:2007 – Flat products made of steels for pressure purposes – Part 7: Stainless steels. Grades 1.4372 and 1.4162 need special approval for use in pressure equipment either according to the Particular Material Appraisal scheme (PMA) or to the European Approval of Materials scheme (EAM) according to the Pressure Equipment Directive (PED).

Thermomechanical treatments

Thermomechanical treatments can be considered as a method to further increase the use and competitiveness of stainless steels. Even the basic CrNi-grades can be hard cold rolled to a desired strength level to optimise their mechanical properties. These cold worked, temper rolled grades are widely standardised both in Europe and in the USA. A typical yield strength level of 500 to 700 N/mm^2 is widely used, e.g. in the production railway cars. In addition to cold working, other strengthening methods like bake hardening (i.e. strain ageing phenomenon) and austenitic grain refinement have been studied intensively since the 1990's. [9-10] Strength increase of 100 N/mm^2 is possible with commercial austenitic stainless steels, like grade 1.4301, by bake hardening. When the suitable combination of steel grade and cold working prior to bake annealing is chosen, the strength increase can exceed values of well above 200 N/mm^2. As the annealing temperature can be kept below 200°C thus avoiding heat tints even without using shielding gas, bake annealing is easily adapted to many cases where the strength of a deformed material shall be increased. Further tailoring of material properties can be achieved by reversion annealing of deformation martensite to fine grained austenitic microstructures. This promising process resulting in fascinating strength ductility combinations, however, is still under development and seems to need more time until it will find its place among the traditional manufacturing methods. [11-12]

Forming applications

As can be seen from the Yearbook of New Stainless Steel Applications of ISSF, stainless steel grade 1.4301 / AISI 304 is still the dominant material for new applications. The occurrence of grade 1.4301 or equivalent even increased slightly from the Yearbook 2006 to the Yearbook 2007. This result contradicts all speculations that predicted that the CrNi-grades would be loosing their market share. However, the share of new applications doubled for the ferritic grades. The price stability of the ferritic grades has most obviously been the driving forces for this development. On the other hand, the CrMn-grades were almost missing in the ISSF Yearbooks indicating that these grades might be used increasingly in conventional high volume consumer products and are therefore not reported in relation to new applications.

Steel grade selection for forming applications

The standardisation of CrMn-grades is in progress in several countries and regions worldwide leading to some difficulties regarding consistency of the material properties between different producers and material availability. Especially some 200-series from Indian producers do not fulfil the requirements of the US market. In Europe, the utilisation of the CrMn-grades has grown, but some uncertainty is caused by several topics, which include:

- Corrosion resistance (e.g. chromium and sulphur content)
- Formability (e.g. austenite stability)
- Scrap value (e.g. manganese and copper content)
- Availability (incl. variations between different producers and even between lots)

The most widely used standard composition of the CrMn-grades is at the moment grade 1.4372 / AISI 201 as listed in Table 3. A wide interest for these materials has led to the development of grades containing increased chromium and nickel levels of 17 % and 4 %, respectively, in order to meet the general requirements for the materials in contact with food. [13]

Table 3. Typical chemical composition of some stainless steels suited for forming applications. Grades 201Cu and 204Cu are Cu-bearing grades and are not mentioned in ASTM A240 as such. The pitting resistance equivalent (PRE) is calculated based on the formula PRE = Cr(wt-%) + 3.3 x Mo(wt-%) + 16 x N(wt-%). Steel designations according to EN 10088-2:2005 and ASTM A240-07.

EN	AISI / UNS	C	Cr	Ni	Mn	Cu	N	Fe	PRE
1.4301	304	0.04	18.2	8.1	1.4	0.3*	0.05	Bal.	19
1.4372	201	0.05	17.2	4.5	6.5	0.3*	0.20	Bal.	20
1.4618*	'201Cu'	0.05	17.2	4.5	6.0	2.0	0.10	Bal.	19
1.4597		0.06	16.5	2.2	7.0	2.2	0.20	Bal.	20
	'204Cu'	0.10	15.2	1.2	8.7	1.7	0.11	Bal.	17
1.4509	S43940	0.02	18.0	0.2**	0.4**	0.1**	0.02	Bal.	18
1.4016	430	0.04	16.2	0.2**	0.4**	0.1**	0.03	Bal.	16

* = A new proposed grade designation ** = Typical residual level of the element.

The ferritic grades listed in Table 3 are the conventional grade 1.4016 with a good availability on the stainless steel markets and the emerging grade 1.4509 that is seen by many as an updated version of the grade 1.4016 for the applications where better corrosion resistance and weldability are required. This relatively new grade is less susceptible to the roping defect that may occur after deep drawing and can hardly be removed by final polishing of the formed product. However, as with most new products, its availability and the appearance of its surface cannot compete with grade 1.4016. In general, the ferritic grades have advantages regarding their mechanical properties when compared to the austenitic grades. They are less prone to springback effects and are easier to cut and work with.

The mechanical properties of some stainless steel suited for forming applications are shown in Table 4. All austenitic grades have rather similar mechanical properties. The higher yield strength of some CrMn-grades is not detrimental for their formability due to their high elongation to the fracture values and their moderate work hardening behaviour compared to the other austenitic grades. This can be seen in Table 5 where all the CrMn-grades reach deep drawing ratios of over two. However, the biggest concern is a phenomenon called 'delayed cracking' or 'seasonal cracking' that has been reported for almost all manganese-alloyed materials and occurs within a few minutes to several days or even weeks after forming. The nickel-content of the steel and the deep drawing ratio correlate clearly when delayed cracking is reported.

Table 4. The minimum values for the cold rolled strip (transverse to the rolling direction) according to EN 10088:2005 and ASTM A240-07. Grades 201Cu and 204Cu are Cu-bearing grades and are not mentioned in ASTM A240 as such. The typical values are only informative and the range is collected from various sources and test data.

EN	AISI / UNS	Rp0,2 N/mm^2		Rm N/mm^2		A80 %		Global standardisation
		EN	Typical	EN	Typical	EN	Typical	
1.4301	304	230	280-300	540	600-700	45	50-60	Fully standardized
1.4372	201	350	350-420	750	650-800	45	45-60	Well established
1.4618	“201Cu”	(220)	300-400	(520)	550-700	(40)	40-60	In progress
1.4597	“204Cu”	300	350-450	580	750-950	40	30-50	In progress
1.4509	S43940	250	280-350	430	500-600	18	20-30	Well established
1.4016	430	260	300-360	450	480-500	20	20-30	Fully standardized

Table 5. Sensitivity to delayed cracking of some austenitic steels as function of the deep drawing ratio measured in the Swift cup tests.

Swift cup test / Deep drawing ratio								
Grade	Ni %	Cu %	1.4	1.6	1.8	2.0	2.12	2.14
1.4301	8.1	0.5	**+**	**+**	**+**	**+**	**+**	**+**
“201Cu”	4.7	2.4	**+**	**+**	**+**	**+**	**+**	
1.4372	4.4	0.3	**+**	**+**	**+**	**--**	**--**	**--**
1.4372	3.6	0.3	**+**	**+**	**--**	**--**	**--**	**--**
“204Cu”	1.1	1.7	**+**	**--**	**--**	**--**	**--**	
+ = Successful **--** = Delayed cracking								

Optimised heat treatments

Changing steel grade to another one is not the only solution for decreasing the costs of the final product. Intermediate annealing that enables multi-phase forming processes is widely used. As alternative, local heat treatments like laser assisted forming and bending processes are suitable techniques when the work hardening of an austenitic grade has to be decreased locally. [14] Local heating methods usually require post-treatments like pickling thus increasing manufacturing costs. Nevertheless, the oxidation behaviour of substitution materials should be studied beforehand because differences are not uncommon. When the local heating methods and even hot forming techniques are used, it can be assumed always that some development work is needed for optimising the production processes.

Conclusions

Volatile nickel prices have made both users and producers of stainless steel seeking for alternative materials to the conventional CrNi-grades. Especially in the year 2007, the reactions on the raw material price developments were relatively strong. Nevertheless, it can be clearly seen that the classic grade 1.4301 / AISI 304 will persist in many applications due to it’s multi-functional properties. However, there exist already several grades that can give enhanced properties and better price stability compared to the conventional grade 1.4301. In the structural applications manganese and nitrogen alloying as well as the use of the duplex, austenitic-martensitic or pure ferritic structure are alternatives. Novel thermomechanical treatments that can partly be applied already to grade 1.4301 have to be taken into consideration, too. For forming applications, there are only a few CrMn-grades and ferritic grades that are worth thinking about, especially when the grade 1.4301 is considered being over-specified. The application of optimized heating treatments are promising methods that should be developed further in order to become strong alternatives to the conventional forming processes. An overview on how to optimise production processes by intelligent material and process selection is given in Figure 2.

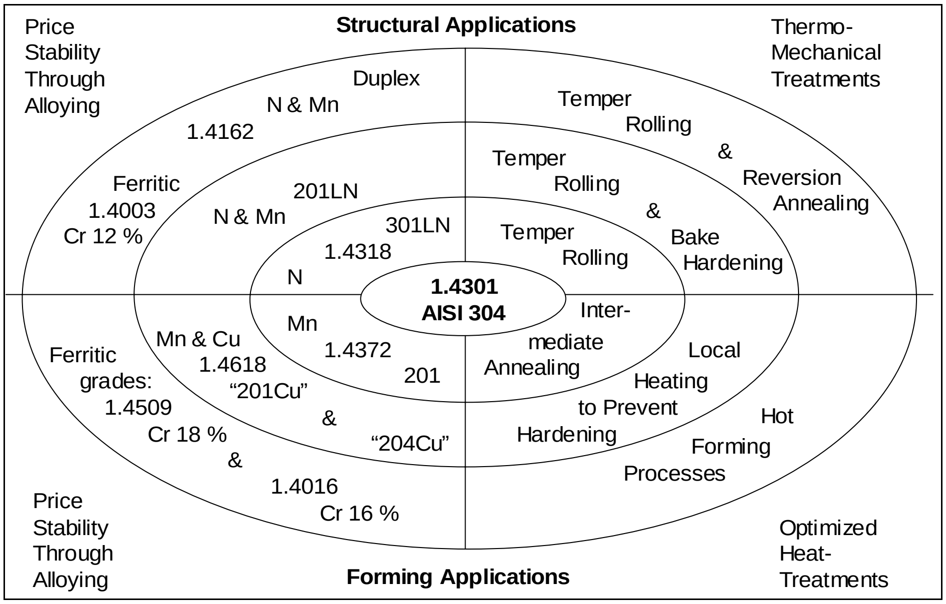

Figure 2. Optimising both material and manufacturing costs by using new alloys and novel treatments.

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ADVANCES IN THE STRUCTURAL USE OF STAINLESS STEEL

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Abstract

The past fifteen years have seen the introduction or major revision of structural stainless steel design codes throughout the world, and at the same time, interest in the use of stainless steel in construction has been accelerating. Historically the high initial material cost of stainless steel has limited its structural use primarily to specialist and prestige applications. However, the emergence of design codes, a better awareness of the additional benefits of stainless steel and a transition towards durable structures and whole-life costing are bringing more widespread use into conventional structures. Although a number of similarities between stainless steel and ordinary carbon steel exist, there is sufficient diversity in their physical properties to require separate treatment in structural design. In addition to the straightforward differences in basic material properties (such as Young's modulus and yield strength), further fundamental differences exist, such as the nature of the stress-strain curve and the material's response to cold-work and elevated temperatures; these have implications at ultimate, serviceability and fire limit states. This paper aims to provide an overview of structural stainless steel design, focussing on the principal differences in structural behaviour as compared to carbon steel, and to highlight recent advances in research. These advances include the generation of a significant pool of structural performance data, broadening of the range of structural applications and scenarios considered (e.g. concrete-filled tubes, fire performance) and exploitation of the cold-working nature of stainless steel.

Introduction

Stainless steel has traditionally been regarded as an extravagant solution to structural engineering problems. Consequently, the use of stainless steel as a primary structural material for conventional construction remains rather limited. Previously, coupled with the high initial material costs, there have been a number of disincentives to adopt stainless steel, including limited structural design guidance, restricted section availability (and no standardisation) and a lack of understanding of the additional benefits of stainless steel amongst structural engineers. However, recent years have seen considerable advancements[1], as summarised in this paper.

Historically, the aesthetics of stainless steel has been an important factor in its specification for structural applications. Consequently, many existing examples of stainless steel structures display a high level of exposed structural members, commonly of tubular cross-section, and are often of a prestigious or landmark nature. Its appeal is principally due to the surface finish and its ability to retain its appearance without deterioration over time, as exemplified by the upper facade of the Chrysler Building in New York (completed in 1930).

The increasing prominence of life cycle costing and life cycle assessment has implications on the use of stainless steel in construction. Cost comparisons made on the basis of the initial material expense of structural components do not necessarily fully reflect the true costs associated with a chosen structural material. An initial life cycle cost comparison of structural metals[2], including stainless steel, including material costs, together with the additional costs of corrosion protection and fire protection, and the longer term costs associated with maintenance and decommissioning has been performed. The study revealed applications, which generally involved exposed structural elements and high costs associated with maintenance, where stainless steel offered the most economic solution on a whole life basis.

There is a wide variety of grades of stainless steel, generated through variation in chemical composition and heat treatment. The most common grades of stainless steel for structural applications are the austenitic and duplex grades. An important feature of stainless steel is its corrosion resistance, enabling its application, unprotected, in a wide range of environments. It should be noted that certain environments, such as those containing high concentrations of chlorides, can be extremely detrimental to the corrosion resistance and resistance to stress-corrosion cracking of stainless steels. In such cases, care must be taken to select suitable grades.

Stainless steels, particularly the austenitic grades, also offer very high ductility and impact resistance. It is therefore particularly suited to applications where ductility and impact resistance are important, such as offshore structures, crash barriers and structures susceptible to blast loading[3], and has already been applied to railway carriage construction. A study into the suitability of adopting stainless steel for structural frames in seismic regions has also been carried out[4], where it was concluded that stainless steel is a viable alternative to carbon steel, but further investigation is required.

Structural performance data

Underpinning the recent development of a number of dedicated structural design codes for stainless steel worldwide has been a significant expansion in the volume of available test data. Although some early structural tests were performed in the 1960s, it was not until the 1990s that widespread structural testing and detailed research into the use of stainless steel in construction commenced. Recent testing programmes have examined stainless steel material response at room temperature[5] and elevated temperatures[6], the behaviour of structural stainless steel cross-sections[5,7], members[8,9,10,11] and connections[12], fire performance[13], and recently low cycle fatigue characteristics. Numerical modelling is also being increasingly used as a tool for the generation of structural performance data.

The focus of much of the experimental research to date has been to generate fundamental test data upon which numerical models may be verified and design rules statistically validated. More recently, with many structural design codes now in place, attention has turned to refinement of existing design methods, development of new design methods and examination of wider applications. A particular feature that has emerged from a number of previous experimental studies has been the importance of cold-work and the associated strength enhancements; these strength enhancements, together with approaches to harness them for structural design are the subject of the next section of this paper. A further means of enhancing loading carrying capacity and improving efficiency of material use, whilst still maintaining the durable and aesthetic stainless steel outer surface, is concrete filled tubes. This area has recently been investigated experimentally[14], where it as found that existing design guidance for concrete filled carbon steel tubes may be safely adopted for stainless steel, whilst proposals for improved formulations were also made.

Exploitation of cold-work

Stainless steel exhibits significant strain hardening, resulting in considerable strength enhancements in response to cold-working. This has been clearly identified in a number of the experimental programmes referred to in the previous section. There are three primary sources of strength enhancements for structural stainless steel components – (1) during the production of the flat sheet prior to section forming, (2) during the section forming operation itself and (3) in service under load.

Strength enhancements during sheet production

Strength enhancements related to cold-working during sheet production have been recently standardised and are now exploited in structural design. When stainless steel is cold-worked, it undergoes substantial strain hardening leading to a significant strength enhancement, whilst adequate ductility is still retained. Following recent experimental and numerical investigations, it was revealed that the design rules for the familiar grades of stainless steel may be safely extended to cold-worked high strength stainless steel material[15,16]. EN 1993-1-4 (2006)[17] now specifies a number of standard cold-worked levels for sheet material, which are defined either in terms of minimum yield strength or minimum ultimate tensile strength and are taken from the European material standard for stainless steel, EN 10088-2 (2005)[18]; for example, CP350 and CP500 have minimum yield strengths of 350 and 500 N/mm^2 respectively, and C700 and C850 have minimum ultimate tensile strengths of 700 and 850 N/mm^2, respectively.

Strength enhancements during section forming

Stainless steel product forms include plate, sheet, strip, tube, bar, cold-formed and hot-rolled structural sections, castings, fasteners and fixings. For structural members, the most commonly used products are cold-formed sections, predominantly because these are the most readily available, require relatively low investment to achieve production capabilities, and are suitable for light structural applications with high structural (and material) efficiency. Cold-formed sections may be created from sheet material either by press-braking or cold-rolling. The strength enhancements induced during the forming process have been noted by a number of researchers, but are not accounted for in existing design methods due to an absence of suitable predictive tools. However, based on a recent experimental programme comprising tensile coupon tests and hardness tests and a compilation of other data, a method for predicting the distribution of 0.2% proof stress around press-braked and cold-rolled stainless steel sections has been proposed[19]. The strength enhancements are related to the properties of the unformed material and to the geometry of the finished section. The achieved enhancements in efficiency are significant and highlight the importance and benefit of harnessing the strength increases that arise during forming of cold-formed stainless steel members.

Strength enhancements under load

A third source of strength enhancements relates to utilisation of strain hardening and plastification under load. The extent of the strength enhancements that may be achieved is governed by the deformation capacity of the structural element. A deformation based design approach – the Continuous Strength Method (CSM) – has been developed[20,21], which employs the deformation capacity of stainless steel structural elements in conjunction with accurate material modelling to rationally exploit its strain hardening characteristics. The method recognises the particular material properties of stainless steel and leads to enhancements in member capacities of about 20% over current design rules, whilst still providing safe-side predictions.

Design guidance

General

Historically stainless steel design rules have been based on assumed analogies with carbon steel behaviour, with modifications made where necessary to fit in with test results. More recently greater recognition has been given to the particular properties that stainless steel exhibits, allowing the generation of more efficient structural design rules. An overview of the provisions of the principal stainless steel design codes (European, US and Australia/New Zealand) was reported by Baddoo[22].

At present, there are no standard sizes for stainless steel sections. Sections are often made to order and most suppliers stock commonly requested geometries. This represents an inconvenience for designers since standard section sizes with corresponding geometric properties and member capacities for differences loading conditions are useful for expediting the design process and subsequent checking. There are however tables and software[23] for common sections sizes based on European design rules.

Design standards

The earliest dedicated stainless steel structural design Standard was published by the American Iron and Steel Institute (AISI) in 1968; the design rules were based primarily on the work carried out at Cornell University. Further research enabled the development of the American Society of Civil Engineers (ASCE) structural stainless steel design Standard, first published in 1991 and more recently in 2002, which effectively superseded the AISI Standard in North America.

In 1995, the Japanese stainless steel structural design Standard was issued; it is only available in Japanese and is focussed on the design of fabricated (welded) sections. Based largely on the Canadian design Standard for cold-formed carbon steel structures, the South African structural stainless steel Standard was published in 1997. In 2001, the Australia/New Zealand design Standard for cold-formed stainless steel structures was issued, and most recently (2006), the European design Standard for stainless steel EN 1993-1-4 was published. The following sub-sections outline various aspects of the structural design provisions of EN 1993-1-4.

Material stress-strain response

The material properties of stainless steel vary with chemical composition and heat treatment (i.e. grade), product type, level of cold-worked, material thickness, direction of rolling (i.e. longitudinal or transverse), and direction of loading (i.e. tension or compression). Although some material Standards simplify matters by grouping cases with similar properties, there remains a wide range of values. For the modulus of elasticity, the European Standard gives a value of 200000 N/mm^2 (compared to 210000 N/mm^2 for ordinary carbon steel) , whilst for minimum yield strength, the European Standard specifies 230 N/mm^2 (for cold-rolled strip of thickness less than 6 mm) and 210 N/mm^2 (for hot-rolled strip of thickness less than 12 mm) for grade EN 1.4301, and 240 N/mm^2 (for cold-rolled strip of thickness less than 6 mm) and 220 N/mm^2 (for hot-rolled strip of thickness less than 12 mm) for grade EN 1.4401, with no variation for anisotropy or non-symmetry of stress-strain response. The shape of the stress-strain behaviour of stainless steel is also fundamentally different from that of carbon steel, necessitating the definition of an 'equivalent' yield point for design, generally taken as the stress at 0.2% plastic strain (i.e. the 0.2% proof stress). Accurate modelling of the rounded material stress-strain curve has also be described by a number of authors[21,24,25], based on extensions of the well-known Ramberg-Osgood relationship.

Element design

The design of stainless steel cross-sections and members follows the familiar carbon steel approach, utilising the concepts of cross-section classification and, for slender elements susceptible to local buckling, the effective width method. The behaviour of stainless steel members differs from that of carbon steel members due to the gradual yielding nature of the material stress-strain curve and variation in other characteristics such as the level of geometric imperfections and residual stresses. Geometric imperfections are generally lower in stainless steel products than equivalent carbon steel products because of tighter controls in the production process to limit the adverse effects of out-of-flatness on aesthetics. Initial analyses of measurements of geometric imperfections in structural stainless steel hollow sections have supported this assertion. Residual stresses have been found to be of similar magnitude to those observed in carbon steel members.

Serviceability

For the determination of deflections in stainless steel flexural members, account must be taken of the non-linear stress-strain characteristics of the material; simply assuming the initial tangent modulus E will result in an under-estimation of deflections. The European, US and Australia/New Zealand design Standards all adopt essentially the same treatment, whereby deflections are calculated based on a reduced modulus of elasticity, taken as the average of the secant moduli in tension and compression corresponding to the maximum serviceability stresses that occur along the member length.

Fire design

The elevated temperature physical properties of stainless steel differ significantly from those of carbon steel, with stainless steel generally exhibiting superior material strength and stiffness retention at elevated temperatures. This is reflected in the current European provisions for the design of stainless steel members in fire, which, other than material properties, largely follow the carbon steel rules. An additional consideration for stainless steel in fire is the thermal expansion. Stainless steel expands to a greater extent than carbon steel, and this leads to greater forces being induced into members that form part of structural assemblages. The relative importance of degradation of material properties (i.e. loss of strength and stiffness) and restrained thermal expansion has been assessed[13]. It was concluded that the level of restraint is crucial when comparing the fire performance of stainless steel and carbon steel, with stainless steel exhibiting superior performance in scenarios of low restraint, but carbon steel performing better in conditions of high restraint.

Conclusions

Significant advances related to the use of stainless steel in structures have been made in recent years, including the publication of a number of major structural stainless steel design Standards. This paper provides of overview of the provisions of these Standards and highlights recent research activities, some of which have already been incorporated into the Standards. Notable recent advances include the generation of a significant pool of structural performance data, broadening of the range of structural applications and scenarios considered (e.g. concrete-filled tubes, fire performance) and exploitation of the cold-working nature of stainless steel.

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BIONIC VAULT STRUCTURED MATERIALS OF STAINLESS STEEL FOR LIGHTWEIGHT APPLICATION AND ENHANCED HEAT AND MASS TRANSFER

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Abstract

Numerous phenomena can be observed in nature, which are a result of controlled self-organization. Bionic vault-structuring is a method to generate a three-dimensional pattern in metallic sheets. Thanks to the controlled self-organization arrangement a minimum of plastic deformation is required for forming the patterns. The surface quality is preserved due to absence of conventional embossing tools. Thanks of their high level of rigidity, vault-structured, hexagonally or very new 3D-facette-structured, components of stainless steel can be produced with greatly reduced wall thickness, and the impact sound is reduced. Vault-structured materials, even if thin and lightweight, are highly resistant to bending and to stressing caused by thermal expansion, and they have other advantageous properties with application potential for lightweight structures. When flow by-passes 3D-profiled surfaces, there is a higher convective heat and mass transfer coefficient compared to smooth surfaces. These synergetic beneficial properties of vault-structured sheet metal of stainless steel were the basis of development and manufacturing of new light-weight-products mostly in close cooperation with manufacturing partners: washing-drum with better flow-characteristics for softer and quicker washing, facing both outer facades and interior walls, where cladding is resistant to indentation, and exterior damage and scratches are hidden visually by the hexagonally or 3D-facette-structured pattern and last but not least a falling liquid heat exchanger and a flow channel with an increased convective heat transfer.
To estimate chances of broader application of vault-structured materials, joining operations have been carried out and tested. It was shown that Cold Metal Transfer (CMT) welding can be applied in order to join vault-structured sheet metals, since the joining process works without mechanical compensation of the height-difference. This is useful for the maintenance process for replacing a damaged vault-structured material.

Keywords: light-weight construction, stainless steel, stiffness, sustainability, self-assembling, vault-structures, enhanced heat transfer.

Introduction

There is a need for sustainability with reduction of material and energy consumption as well for beneficial properties of the products with high quality for the consumer. But in past times sustainability conflicted with quality.

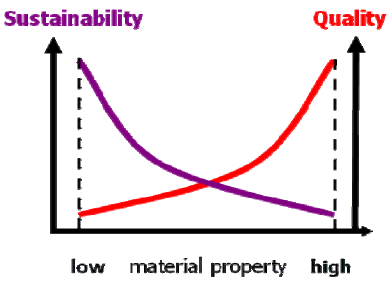

Figure 1. Sustainability versus quality [1]

One approach in the design of sustainable products is the transfer of evolutional principles of nature into technical applications. The comparison of the traditional technical way of producing products with the biological way for producing equivalent products demonstrates the need of learning from nature.

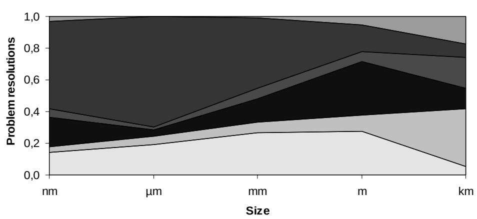

Figure 2. Technical way / required features and resources [2]

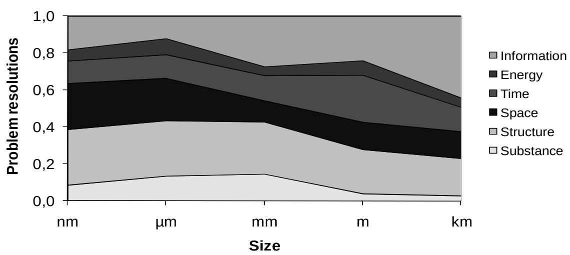

Figure 3. Natural way / required features and resources [2]

The following question could be asked: How is it possible that that forming processes in nature are much more efficient than man-made techniques? As shown in figure 3 nature can reduce approximately half of the substance and at least 1/10 – 1/20 of the energy consumption needed compared with man-made techniques.
So that is a great stimulation and challenge for technical processes to learn from nature.
One approach in learning from natural principles is our transfer of evolutional principles of physics into technical application. Sustainable development is a holistic approach harmonizing ecological, economical and socio-political needs with respect to the superior objective of enhancing human living standards while improving the availability of natural resources and ecosystems for future generations to meet their own needs. Therefore the use productivity of natural resources has to be raised for achieving a higher availability without exceeding ecological limits [3].

One approach for increasing the use productivity of natural resources is lightweight construction. Lightweight construction means to preserve or even expand a product’s functionality while the overall weight of the product decreases. Approaches for reducing masses are to apply less dense materials, e.g. metal foams and composite materials, or to decrease the applied materials volume by reducing wall thicknesses. By this less material has to be applied in total. In both cases less energy is needed for transportation of the ready-made product, so that the ecologically friendly aspect of lightweight construction is supported [4].
Unfortunately, reducing wall thicknesses often leads to a loss of inherent stability of applied parts. The stiffness of thin walled parts is regained by reinforcement elements. For parts made of sheet metals, like automotive or aeronautical body parts, this often is achieved by applying beads or folds to the flat material. However the material is highly plasticized and the surface quality is changed by applying these traditional forming processes and does not fullfil the requirements of sustainability (see Figure 2, Figure 3).
Our approach to increase the more-dimensional rigidity is to structure flat materials with bulges in a very effective but gentle way. This has been applied in the technology of vault-structuring on a basis of controlled self organization.

Vault Structuring Process

In the process of vault-structuring, thin walled sheet metals are formed into repetitively arranged bulges. For structuring metal sheets, these are bent around a cylindrical core with protruding stiff supporting elements as shown in Figure 4. By applying pressure onto the outer side of the thin walled cylinder, the material moves inward into the spaces between the supporting rings. When a critical pressure is reached, the material spontaneously "plops" into an enduring state of repetitively arranged rectangular structures. The main characteristic is that the arranged horizontal folds of the bulges are created by controlled self organization because there are no supporting rings underneath in horizontal direction (Figure 4). The corrugated rectangular structures in Figure 4 do not yield the optimal shape to receive a high stiffness in all directions. By using flexible supporting rings hexagonally bulges may be formed by self organization / bifurcation [5]. Thus new structures are created by the principle of energy minimization.

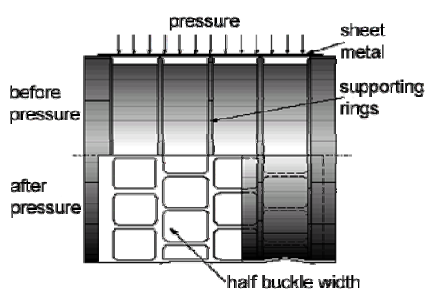

Figure 4. Basic vault-structuring process [5]

In order to compensate inevitable inhomogeneities in the wall thickness, the material itself and the geometrical condition, the basic structuring process was technically modified. So even sheet metal can be more-dimensionally formed far into the “third dimension”.

The vault-structuring process was modified and a continuous working machine has been developed for structuring and straightening plates or coils of all kinds of thin material and patented. Figure 7 shows the at present deliverable metal sheet characterised by the width over hexagonal structure: 33mm and 50mm on the right hand side hexagons with straight folds and 17mm and 39mm on the left hand side hexagons with swung folds. These metal sheets are deliverable up to a width of 1100mm and a wall thickness of up to 1,0 mm.

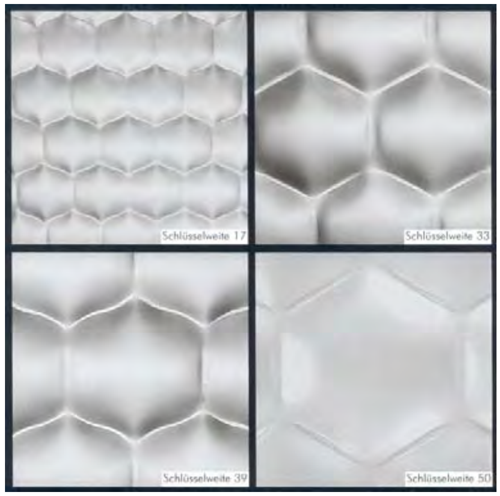

Figure 5. Available vault-structured sheet metal of stainless steel

In a new secondary technical evolution process the facetted structured sheet metal was invented. The remarkable fact is that plane surfaces are created which are assembling themselves to trihedral pyramids [6].

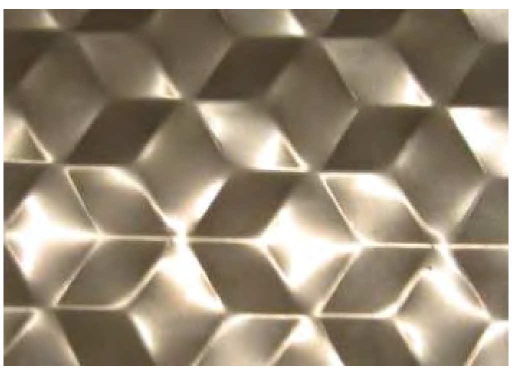

Figure 6. Facetted structured sheet metal

Stiffness Porperties of Vault Structured Materials

The most relevant benefit of the vault-structured material is the gain of stiffness in all directions compared to unstructured material. Some comparative studies surveying the stiffness properties of unstructured, vault-structured and other structured metal sheets have been carried out [5].
As an example, Figure 7 shows a comparison between flexural strength tests of smooth, conventional embossed (“knobbed”) sheet metal strips and vault structured sheet metal strips [7].

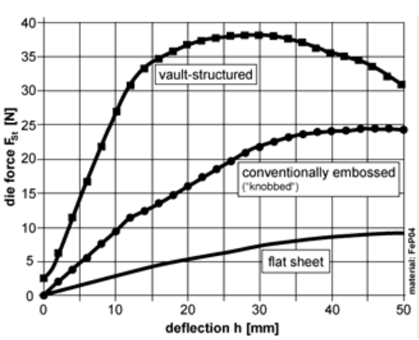

Figure 7. Flexural strength test of even, conventional embossed (“knobbed”) and vault-structured sheet metal using ductile steel FeP04

Although the vault-structured sheet metal is the least plasticized, it still has a much higher flexural strength than conventional embossed sheet metal. In addition, the improved stiffness of vault structured sheet metals is achieved with significantly less energy consumption in the manufacturing process [7].
Using steel with high tensile strength, the gap between the high flexural strength of the vault-structured sheet metal strip and the conventional embossed ("knobbed") sheet metal strip is much greater.

Characterization of vault structured sheet metal

The localized degree of deformation along the structure results not only from the material characteristics and the wall thickness, but also from the complex shape of the vault structure itself. Therefore some individual material cuttings and material tests are required for the characterization. The degree of deformation can be calculated by using Vickers micro hardness testing because the material hardness is roughly proportional to the plastification. The measurement procedure is described as followed:
At first a correlation between the deformation and the tensile strain has to be analyzed. The determination of the mechanical characteristics takes place using the tensile test for smooth sheet metal as per DIN 50114. The tensile tests on non-structured sheet metal within the intervals of tensile up to the point of shear (equivalent to 100% plastification) are measured. Afterwards the sample of sheet metal is cut in the middle into small strips, ingrained, ground and polished. Then the Vickers micro hardness test is measured on the edges of the strips. So a correlation between Vickers hardness and the deformation can be evaluated. Additionally, the Vickers hardness and deformation were analyzed on vault structured samples of sheet metal in order to determine the local degree of plastification.
Figure 8 shows the cuttings of vault structured sample of DX56D steel. The cuttings A and B represent cuts transverse to the folds whilst cuts C and D show cuts parallel to the folds.

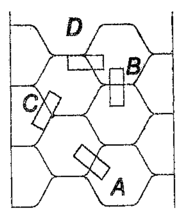

Figure 8. Cuttings of vault structured sample for material tests

In Figure 9 the individual Vickers micro hardness values are shown as a function of the localized measure points (trough, fold, trough) of the vault structured sheet metal. The markings refer to the cuts A, B, C, and D in Figure 8. The dotted lines show the Vickers micro hardness with reference to the degree of plasticizing corresponding to the absolute tensile in %.
For the deep-drawn steel DX56D, sheet metal with structure sizes SS 33 mm (Figure 9) has been tested. The maximum tensile in the fold area is measured as about 11%. The tensile in the trough areas was less than 2%. These values refer to absolute tensile. The absolute ductile yield for DX56D was 38%. These material tests confirmed the minimal plasticizing of vault structured materials.

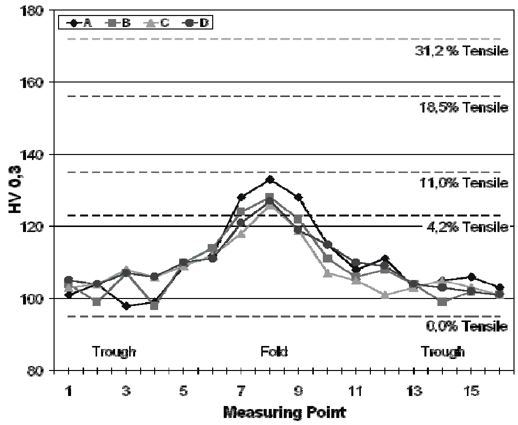

Figure 9. Vickers micro hardness values and tensile values (DX56D, SS 33mm)

Exemplary processing and products

Some secondary processes and final products based on vault-structured sheet metal of stainless steel have been realized.

Figure 10 shows a comparison of a vault-structured and an unstructured sheet metal which are spot welded on a frame. Usually instabilities and dislocations emerge when thin walled sheet metal is welded. This is due to hindered thermal expansion (see on the right hand side of Figure 10). On the left hand side of Figure 10 no dislocations occur in the vault-structured sheet metal. The reason of this can be found in a compensating behavior in the direction of the sheet metal and an enhanced bending stiffness.

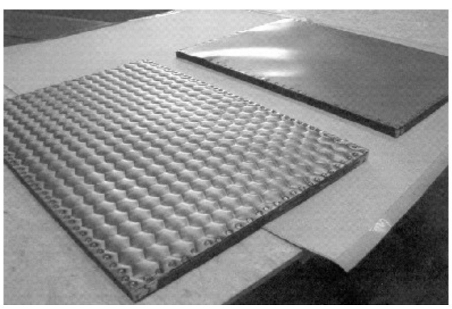

Figure 10. Vault-structured sheet metal of stainless steel spot welded on a frame

Figure 11 shows a vault-structured plate of stainless steel for fire protection of a body part in a train. The plates are very rigid for a reduction of weight. Furthermore the plate is flexible enough to withstand stresses in case of thermal expansion. For a water proofed welding seam the edges of vault-structured sheets are equipped with additional very small structures.

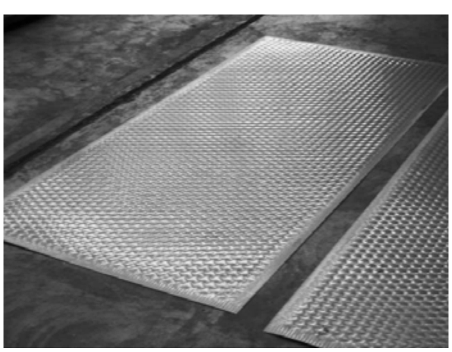

Figure 11. Vault-structured plate of stainless steel for fire protection in trains

To estimate chances of broader application of vault-structured materials, joining operations have been carried out retaining the vault-structured design.

The testing set-up referred to potential applications, e. g. in railway applications. In case of damages to single spots of the body parts of railway cars, not the whole body part has to be replaced. The damaged material can be cut out and replaced with an adapted piece of metal sheet. Since welding is the primary joining technique in this field of application, multiple automated welding methods like MAG or the new Cold Metal Transfer Process (CMT) by Fronius [8] where investigated. Due to the large variety of different joint types for mating sheet metal parts, two representative configurations where chosen for preliminary testing. In the first case, vault-structured sheets where welded onto a non-structured frame material. In the second setup, two vault-structured sheets where welded together along a butt joint. Since gaps between the joining pieces are inevitable in both cases due to the vault-structured material, the challenge is in the varying height of the gap as well as in the different distance of the welding spot from the processing head.

Within the testing environment it was shown that Cold Metal Transfer (CMT) welding can be applied in order to join vault-structured sheet metals, since the joining process works without mechanical compensation of the height-difference. In Figure 12, different states of the maintenance process are shown for replacing a damaged vault structured material.

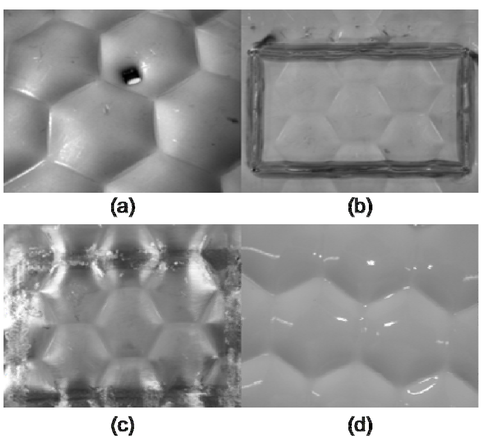

Figure 12. Welding tests using Cold Metal Transfer welding: (a) damaged vault-structured part, (b) substitution part welded in, (c) weldment joint after grinding, (d) repaired area after varnishing

Figure 13 shows the different light reflections of stainless steel façade panels. Only when the panel is absolutely flat the reflection is uniform. On the bottom panels with only slight deformations the reflection is very irregular

Figure 13. Panels of stainless in of hotel facade

Figure 14 shows the comparison of a flat and a vault structured sheet of stainless steel. As it can be observed the scratches and dents are visible on the flat material but are masked by the vault structures.

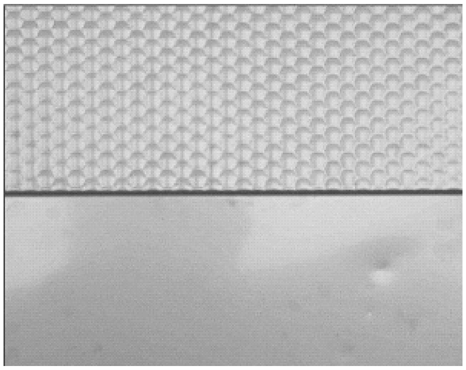

Figure 14. Comparison of unstructured and vault structured panel

Figure 15 shows a sports hall in Odessa. The curved roof consists of 6000 square meters of vault structured pre-coated sheet metal. This project was honored with the "Deutscher Materialeffizienzpreis 2006" (German award of material efficiency).

Figure 15. Sports hall with vault structured roof

Figure 16 shows an example of vault structured stainless steel used for furniture. Scratches and fingerprints are not visible on this desk.

Figure 16. Vault structured desk of stainless steel

Figure 17 shows a washing drum of Miele made of hexagonally vault-structured stainless steel with synergetic characteristics such as advantageous flow behavior of the water along the vault-structured surface for a more gentle as well as quicker washing process, high form rigidity as well as an attractive design.

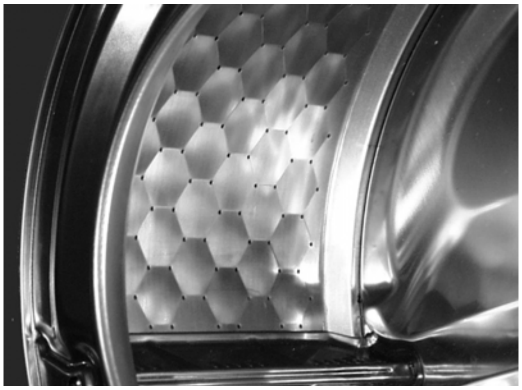

Figure 17. Washing drum [picture: Miele]

Enhancement of Heat Transfert

The convective heat transfer is highly enhanced when a liquid flows over hexagonally vault-structured or facetted-structured surfaces of sheet metal. Every single structure initiates a separation of boundary layers that results in a increased convective heat transfer coefficient compared to smooth surfaces. The measurements of the local convective heat transfer at the individual vault-structures on the wall were taken employing by an electric current (Joule heat). An evenly distributed heat source is generated and measured in the wall because the wall thickness of the hexagonally vault-structured or facetted-structured sheet metal of stainless steel is unchanged during the vault-structuring process. If one side of the electrically heated wall is completely heat-insulated, the local heat transfer coefficient can be calculated when the local wall temperature is measured and the bulk fluid temperature is calculated or is also measured [9].
The enhanced heat transfer will be demonstrated on two examples.

Figure 18 shows thin film flowing across the facetted-structured sheet metal of stainless steel.

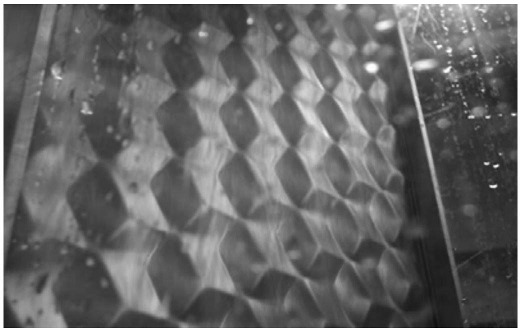

Figure 18. Thin film flowing across the facetted-structured sheet metal [10]

The diagram in Figure 19 shows the largest local convective heat transfer coefficient h (in the center of each structure) versus Re numbers. Using facetted-structured or hexagonally structured sheet metal the convective heat transfer is doubled compared to smooth walls.

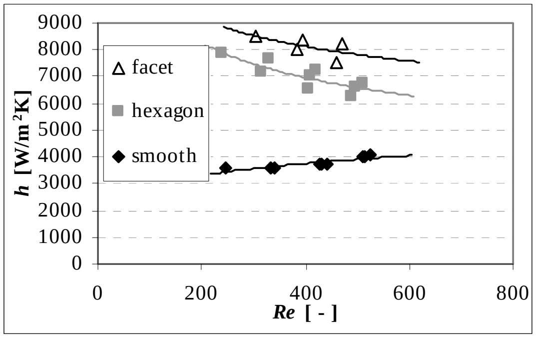

Figure 19. Largest local convective heat transfer coefficient h versus Re numbers [10]

The diagram in Figure 20 shows the largest and the average local convective heat transfer coefficient h (in the center of each structure) against Re numbers.

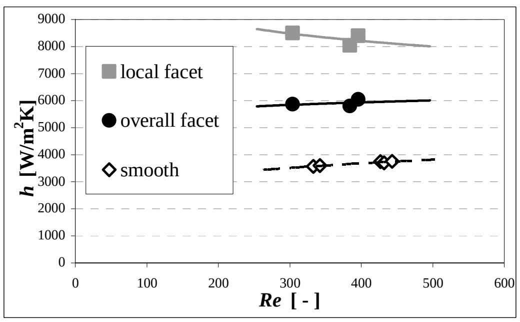

Figure 20. Local and average convective heat transfer coefficient h versus Re numbers [10]

Figure 21 shows a conduit consisting of hexagonally vault-structured sheet metal of stainless steel. Inside of the conduit flows water in the turbulent regime.

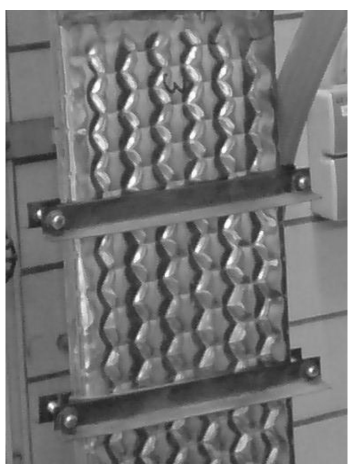

Figure 21. Conduit of vault-structured sheet metal of stainless steel [11]

Figure 22 shows the convective heat transfer coefficient h versus the length of the conduit when water flows in hexagonally vault-structured conduit of stainless steel at Re number 30000.

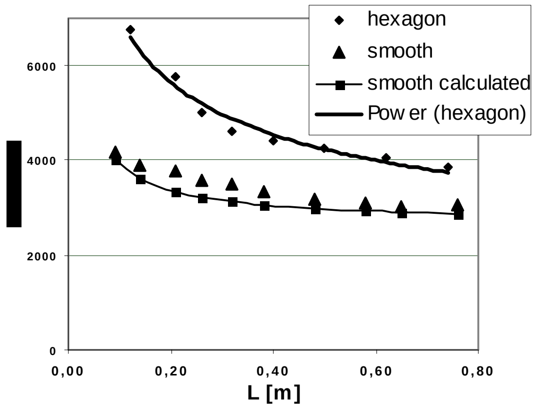

Figure 22. Convective heat transfer h versus the length of the conduit at Re number 30000 [11]

Summary

Vault-structuring on the basis of self-organization and energy minimization is a method to improve the stiffness of sheet metals for lightweight applications. In comparison to conventional unstructured materials, this enables saving material and energy, both in production and during the usage phase of products designed with regard on sustainability.

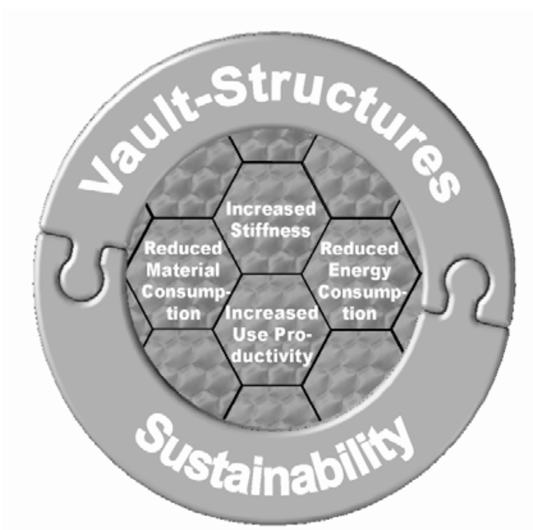

Figure 23. Vault-structures for sustainable development

Vault-structured sheet metal offers synergetic properties, especially a high flexural strength, a better stability in the case of stresses by thermal expansion, non glaring light reflection with additional camouflage of scratches and increased heat and mass transfer in case of liquid flowing along the surface of vault-structured sheet metal.

Concerning sustainability, vault-structured materials are predestined for lightweight construction applications due to the improved stiffness of structured materials, which allow decreasing the applied materials volume by reducing wall thicknesses. Increased heat and mass transfer of structured materials allow higher efficiencies in heating, ventilation and air-conditioning applications. In addition, the vault-structuring process itself is energetically highly efficient and therefore suitable for sustainable manufacturing processes.

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DESIGN AGAINST BRITTLE FAILURE FOR STAINLESS STEELS IN THE EUROPEAN PRESSURE VESSEL CODE EN 13445

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Both specific rules as well as proper materials data have been lacking concerning design against brittle failure. This has been of major concern particularly in safety classed components such as pressure vessels. To solve this problem, new methods for design against brittle failure based on fundamental principles in fracture mechanics have been developed. Elasto-plastic fracture mechanics is fully implemented by taken failure limit diagrams into account. A unique feature is that both primary and secondary stresses such as residual stresses are considered.

By using the Master curve approach basic relations between the fracture toughness and the impact toughness can be established. This implies that the code requirements can be based on impact toughness values and expensive fracture mechanics testing can be avoided in engineering applications. A critical issue is the minimum crack size that can be safely detected by non-destructive measuring techniques. By analysis of available scientific literature, relations between the minimum safely detectable crack size and the component thickness have been set up. The new approach has been verified experimentally with the help of a large number of fracture mechanics tests.

The new design principles are being implemented in the European pressure vessel code EN 13445, part 2, Materials. In the present version of EN 13445 there are some severe limitations concerning the use of high strength steels. In fact, steels with yield strength above 460 MPa cannot be used without performing detailed fracture mechanics analysis and duplex stainless are not allowed in gauges above 30 mm, which excludes many modern high strength steels with good toughness properties. This is now modified.
In the paper it is explained how the code EN 13445 handles design against brittle failure. It is demonstrated that the code takes into such factors as the component thickness, stress level, weldment, the material strength and impact toughness, as well as heat treatment.

Keywords: duplex stainless steel, pressure vessel, welding, fracture toughness, design principle, EN13445.

Introduction

It is well well-known that failure of pressure vessels can have severe consequences giving human damages, destruction of equipment and down time in the production. The risk for brittle failure increases with decreasing operating temperature, component thickness and low material toughness. Vessels in ferritic steels operating at low temperatures have always been of special concern, because many failures have taken place in the past. It has been demonstrated that the same design principles against brittle failure apply to duplex stainless steels as for ferritic steel [1]. Consequently, design against brittle failure for duplex stainless steel has to be handled with the same care as for ferritic steels. For austenitic stainless steels, brittle failure is normally of concern only at very low temperatures.

The codes for design against brittle failure were empirical in nature in early developments. In the 1980's, the first models based on fracture mechanics appeared. In two countries such models [2], [3] were used to develop national codes, namely in France (CODAP) [4] and in Sweden (Swedish pressure vessel code) [5]. These codes represented a major break through because it made it possible for the first time to understand the influence of important factors. For example, the effect of changing the thickness, service temperature, toughness and strength of the steel on the risk for failure could be computed. In addition, the difference between parent metal, as-welded material and post weld heat treated material could be taken into account in the Swedish work.

For the European pressure vessel standard, which is now designated EN 13445 the model [3] was taken as a part of the basis for design against brittle failure. Due to the non-uniformity of the existing national codes, the development of the European code took a long time. The Subgroup "Low Temperature" of the Joint Working group Materials (JWG-B) of the CEN TC 54 committee was responsible for the work. The development is summarised in reference [6]. The design against brittle failure is placed in Annex B of EN 13445 [7]. A corresponding code for steel structures "Fracture avoidance concept for steel structures" - in prEN 1993-2 (Eurocode 3) [8], [9] has been developed also based on fracture mechanics.

Important fracture mechanics tools have been established since the model [3] was published. These include the master curve concept [10] and the Failure Assessment Diagram (FAD) [11]. Valuable results have also been generated in the European projects SINTAP [12] and ECOPRESS [13]. It was evident that EN 13445 [7] should be revised to take these new developments into account.

The purpose of the present paper is to present a new version of the code [14], describe the principle layout of the code and discuss some of the differences in comparison to the previous version.

Survey of the methods in the code

The code EN 13445 [14] presents three alternative methods for design against brittle failure in pressure vessels. The use of anyone of these methods is sufficient. It applies to steels in varies product forms used in pressure parts: plate, strip, tubes, fittings, forgings, castings, flanges, fasteners and weldments. A minimum design temperature is given based on impact energy requirements for the base material, heat affected zone and weld metal, which is assumed as an essential safety requirement.

Method 1. Maximum component thickness and minimum design temperature

Method 1 consists of different parts depending on material
a) For C and CMn steels with a yield strength $\leq$ 460 MPa, the minimum design reference temperature T_R is assumed to be equal to the one where the impact energy is specified to be 27 J (T_{27J}).

$$T_R = T_{27J} \qquad (1)$$

The temperature T_{27J} should be taken from a harmonised European material standard. The impact energy should also be possible to achieve after fabrication in any part of the vessel. Related quality measures have to be undertaken by the fabricator. The maximum component thickness is calculated according to the same principles of fracture mechanics as used for Method 2.

b) For Ni-alloyed steels with 3% to 9% nickel the minimum design temperature is in general the same as the one where impact energy requirements are specified.
c) If austenitic steels are used below -105 ºC, impact energy requirements of 40 J for the weldments should be verified. Austenitic stainless steels such as 304 and 316 may contain ferrite. If such steels are used at or below -196ºC, impact energy requirements of 40 J should also be verified at -196ºC for the parent material.
d) Special rules apply to bolts and nuts.

Method 2. Minimum design temperature as a function of thickness

Method 2 applies to two types of materials: i) C, CMn and low alloy ferritic steels with a minimum yield strength $\leq$500 MPa and ii) duplex stainless steels with a minimum yield strength $\leq$ 550 MPa.

Method 2 is a more general approach than Method 1 for the types of materials that it is applicable to. It can be applied to a wider range of thicknesses and temperatures than Method 1. The restriction in Eq. (1) no longer applies. T_R can be smaller or larger than T_{27J}.

Method 2 is fully based on principles of fracture mechanics. A safety factor of 25 K is added. The scientific details are given in [1] and summarized below.

Method 3. A priori fracture mechanics analysis

According to this method the designer can use any of the established scientific methods in fracture mechanics including the one presented in [1] to ensure that brittle failure will not occur during the operation of the vessel. This gives the designer larger flexibility than in Methods 1 and 2. Expert knowledge in fracture mechanics and the design of pressure vessels is essential.

Cases not covered by Methods 1 or 2 can be handled. Method 3 can also be used to justify deviations from the requirements of Method 1 or 2. Only general guidance is given. This method should only be used when concerned parties agree. This method will not be discussed in the present paper. For more information, see for example [15].

Each of the three methods may be used independently. It is only necessary to satisfy the requirement of any one method.

Temperature adjustment for low pressure

If a vessel is operating at lower pressure than the maximum design pressure, the risk for brittle failure can be significantly reduced. This can be expressed with the help of the temperature adjustment T_S

$$T_M = T_R - T_S \tag{2}$$

T_M is the minimum metal temperature that is allowed. In the code values for the minimum design reference temperature T_R is given, which is independent of the any possible temperature adjustment T_S. Using the model in [16], T_S can be computed. The result is shown in Table 1 in the middle three columns. There is a distinct difference between post welded heat treated (PWHT) and as welded (AW) conditions. In the PWHT conditions most of the residual stresses are removed but not in the AW condition. Consequently, the temperature adjustment is insignificant in the AW condition.

The last column is based on the fact that the risk for brittle failure is low at very low stress levels. This is well established both experimentally and from operating experience. However, the implementation of the calculation model for temperature adjustment is yet under discussion.

Table 1. Temperature adjustment T_S

	Ratio of pressure induced principal membrane stress and maximum allowable design stress			Membrane stress
Condition	> 75 %	50 - 75 %	≤ 50 %	≤ 50 MPa
Non welded or post weld heat treated condition	0 °C	+ 10 °C	+ 25 °C	+ 50 °C
As welded condition when thickness < 30 mm	0 °C	0 °C	0 °C	+ 40 °C

Method 1 for austenitic stainless steels

Parent metals of stainless steels listed in Table 2 can be used down to a metal temperature specified in the table in solution heat treated condition without impact testing. The exception is when impact testing is required by the material standard. As an example according to EN 10028-7 impact testing at room temperature must be performed for plates in cryogenic applications (below -75 °C) for thicknesses above 20 mm.
The distinction between the two minimum metal temperatures in Table 2 is essentially based on the possibility of presence of ferrite. The impact toughness of austenitic stainless steels is approximately temperature independent down to low temperatures where even small amounts of ferrite give a reduction of the toughness. For fully austenitic steels in the first category this effect does not appear. The steels in the second category can sometimes contain ferrite and in particular this is the case for the cast steels in the third category.

Table 2. Austenitic stainless steels and their lowest minimum metal temperature T_M

Material	T_M (in °C)
X1NiCrMoCu 31-27-4, X1CrNiMoN 25-22-2, X1CrNi 25-21, X2CrNiMoN 17-13-3, X2CrNiMoN 17-11-2, X2CrNiMoN 18-12-4, X2CrNiMo 18-15-4, X2CrNiN 18-10, X2CrNiMo 18-14-3, X2CrNi 19-1	– 273
X6CrNiTi 18-10, X1CrNiMoCuN 25-25-5, X1NiCrMoCuN 25-20-7, X1CrNiMoCuN 20-18-7, X1NiCrMoCu 25-20-5, X2CrNiMoN 17-13-5, X6CrNiMoTi 17-12-2, X3CrNiMo 17-13-3, X6CrNiMoNb 17-12-2, X2CrNiMo 17-12-3, X5CrNiMo 17-12-2, X2CrNiMo 17-12-2, X6CrNiNb 18-10, X5CrNi 18-10a, X2CrNi 18-9	– 196
GX5CrNi9-10, GX5CrNiMo19-11-2, GX2NiCrMo28-20-2, GX2CrNi19-11, GX2CrNiMo19-11-2	– 196

Special requirements for weldments have been formulated since in the weld metals ferrite can be present in the microstructure. Where the design temperature is below -105 °C, impact toughness of 40 J must be satisfied for weld metal and heat affected zones. If testing has to be performed, it is performed at -196 ºC.

Theoretical background to Method 2

Stress across crack

The basic fracture mechanics criterion for avoiding brittle failure is

$$K_I \le K_{Ic} \tag{3}$$

where K_I is the stress intensity and K_{Ic} the fracture toughness. The stress intensity can be expressed as

$$K_I = \sigma_{appl} \cdot \sqrt{\pi a} \cdot Y \tag{4}$$

σ_{appl} is the stress perpendicular to a surface crack of depth *a*. *Y* is factor that depends on the geometry of the crack and the component. For the cases of interest in the code, *Y* is close to unity [16]. Post weld heat treatment is rarely used for duplex stainless steels and the case of interest is the as-welded condition. The applied stress $\sigma_{appl\ AW}$ is given by

$$\sigma_{appl,AW} = R_{p0.2,nom} + \sigma_{shift} \tag{5}$$

where $R_{p0.2,nom}$ is the nominal minimum yield strength given in material standards. To reach the typical level of the yield strength, a strength shift σ_{shift} = 100 MPa is added.

Maximum crack size

The maximum crack depth should be selected in such a way that any larger crack should safely be detected with modern non-destructing testing techniques (NDT). Initially it was assumed that the maximum crack depth was a quarter of the wall thickness *t* [3]

$$a = t/4 \tag{6}$$

However, it has later been recognised that this is not conservative enough for small cracks. To take this into account the expression for the maximum crack depth has been modified [1]

$$a = \Theta_0(t)t \tag{7}$$

$$\Theta_0(t) = 1 - \frac{3}{4}\tanh(\frac{t}{t_0}) \tag{8}$$

t_0 is a reference thickness. The function $\Theta_0(t)$ is equal to unity at small thickness and equal to 1/4 at larger thicknesses. t_0 is related to t_{50}, which is the thickness where a crack depth of half the thickness can be detected with NDT.

$$t_{50} = t_0 \cdot \text{atanh}(2/3) \tag{9}$$

In EN 13445 it has been decided to use t_{50} = 10 mm, and consequently t_0 is 12.4 mm. There is another possible deficit with Eq. (6). It can be expected to give over conservative results for larger thicknesses. To avoid this, Eq. (8) can be generalised [22]

$$\Theta_{lim}(t) = \frac{0.5t_{50}}{t}\tanh(\frac{\Theta(t)t}{a_{lim}}) / \tanh(\frac{0.5t_{50}}{a_{lim}}) \tag{10}$$

where a_{lim} =25 mm. The function Θ_{lim} is shown in Figure 1.

In Figure 1 comparisons are made to studies of crack detection capabilities of NDT techniques. Eq. (10) is obviously conservative relative to the observations, except for one set of observations at thinner gauges. It t_{50} is increased to 20 mm the expression is conservative relative to all observations. With the help of Eq. (10) it is possible to justify that slightly less restrictive values than given by Eq. (6) can be used at thicker gauges.
A t_{50} value of 10 mm gives approximately a 20ºC lower design temperature for gauges less than 30 mm than t_{50} = 20 mm. This difference is about 5ºC for a wall thickness of 50 mm and can be disregarded for larger thicknesses.

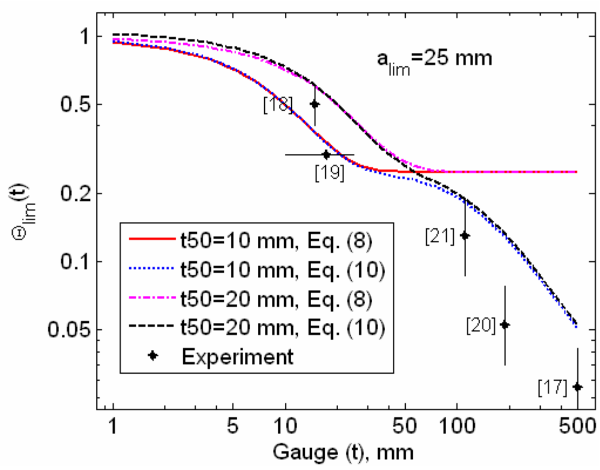

Figure 1. The functions $\Theta_0(t)$ and $\Theta_{\lim}(t)$ ($a_{\lim}$ = 25 mm) versus thickness t according Eqs. (8) and (10) for the t_{50} values 10 and 20 mm. Crack detection observations with their references are included.

Fracture toughness

In Eq. (3) the experimental value for the fracture toughness K_{Ic} could be used. Unfortunately, K_{Ic} is tedious and expensive to determine and thus it is rarely available for individual heats. Instead, impact toughness values are used. Fortunately for ferritic and duplex stainless steels, the two types of toughness can be related to each other [16]

$$T_{\mathrm{K100}} = T_{27J} + C \tag{11}$$

T_{K100} is the temperature where the fracture toughness $K_{\mathrm{I}c}$ is 100 MPa√m and T_{27J} is the Charpy V impact transition temperature for an impact energy of 27 J. C = -18 ºC is a constant. The verification of Eq. (11) for duplex stainless steels can be found in [22]-[24].
Wallin [25] derived an expression for the temperature and thickness dependence on the fracture toughness, which is sometimes called the Master curve [26].

$$K_{\mathrm{c}} = 20 + \left[11 + 77\exp\left(\frac{T_{\mathrm{M}} - T_{\mathrm{K100}}}{52}\right)\right]\left(\frac{25}{t_{\mathrm{eff}}}\right)^{1/4}\left(\ln\frac{1}{1-p_{\mathrm{f}}}\right)^{1/4} \tag{12}$$

where t_{eff} is the effective thickness in mm (= total crack front length), and p_f the failure probability.

Failure criterion

The failure criterion in Eq. (3) is somewhat simplified. In fact both the role of residual stresses and of plasticity effects should be taken into account. It turns that the net effect of these two contributions is small (~ 5 ºC) and they are not discussed further here. For a detailed analysis, see [1] and [16].

Method 2 for duplex stainless steels

Method 2 applies to ferritic steels and to DSS with yield strengths ≤ 500 and ≤ 550 MPa, respectively. Based on the expressions in section 4, a minimum design temperature T_R is derived as a function of specification temperature T_{KV} for the impact energy and the thickness. In Method 2, T_R may be lower or higher than T_{KV}. A distinction is made between as-welded (AW) and post weld heat treated (PWHT) conditions. Since post weld treated condition is rarely used for duplex stainless steels only values for the as-welded (AW) condition are given in the standard. These values should be satisfied for both parent material and weldment independent of heat treatment condition.

The minimum design temperatures T_R for duplex stainless steels in EN 13445 are shown in Figures 2 to 4 for the yield strength values 385, 465 and 550 MPa. The code values are identical to the values from the model described in section 4. T_R is given as a function of impact transition temperature T_{KV}. For DSS, T_{KV} is taken for 40 J.

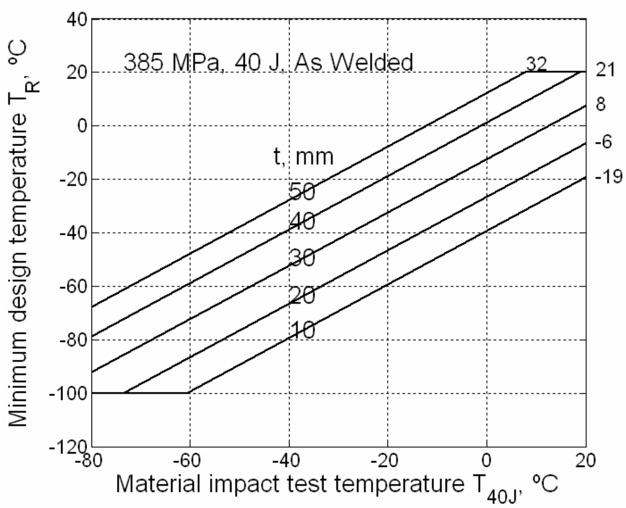

Figure 2. Model values for min design temperature T_R versus temperature where the Charpy impact toughness is 40 J. Values are given for wall thicknesses *t* between 10 and 50 mm. The yield strength is assumed to be 385 MPa, which corresponds to the values for DSS 2304.

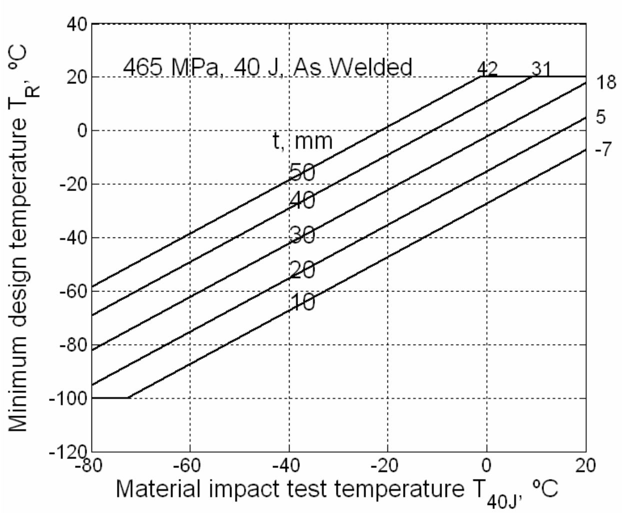

Figure 3. Same as Figure 2 for a yield strength of 460 MPa representing the DSS 2205 and LDX 2101

The curves are given for the thicknesses 10, 20, 30, 40 and 50 mm. 50 mm is the maximum gauge that is allowed in the draft version of the code. For thickness below 10 mm, the curve for 10 mm is used. Linear interpolation between the different thickness levels is allowed. Alternatively the next higher thickness can be used. Linear interpolation between the strength levels in Figures 2 to 4 can also be performed. Again, alternatively the next higher strength level can be considered. If the impact test temperature is specified for 27 J instead of for 40 J, 10ºC should be added to T_R. Extrapolations for temperature ranges, thickness ranges or strength levels beyond the values in Figures 2 to 4 are not permissible.

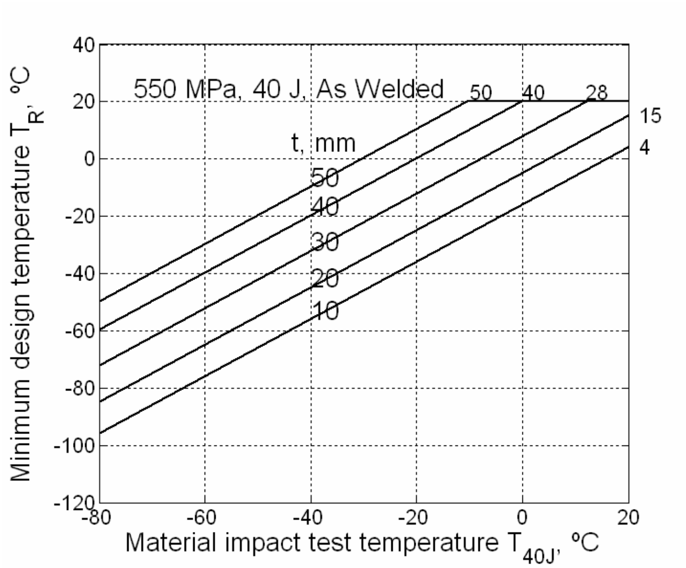

Figure 4. Same as for Figure 2 for a yield strength of 550 MPa representing the steel 2507

It is evident that all the curves for T_R in Figures 2 to 4 can be expressed in the form (all temperatures in ºC)

$$T_R = T_{40J} - 20 + C \qquad -100 \le T_R \le 20 \qquad (13)$$

where C is a constant. The value of C in ºC is given on the right hand side of each curve. Thus, in spite of the complexity of the theory, the end result has a very simple form. A cutoff is introduced at -100 ºC, so lower design reference temperatures than -100 ºC are not allowed. In a similar way a cutoff is present at 20 ºC. Design reference temperatures above 20 ºC can not be used.

$T_R \simeq T_{KV}$ is approximately satisfied for a thickness of 40, 30, and 25 mm at the strength levels 385, 465, and 550 MPa, respectively. Thus, the design reference temperature is reduced with increasing strength of the materials. Below these thickness values, $T_R < T_{KV}$ and above $T_R > T_{KV}$.

The temperature adjustment in Eq. (2) also applies to Method 2.

Verification of the model

An obvious first hand choice to verify the design procedure would be to perform full scale pressure vessel burst tests. However, such tests are expensive and there are few places where they can be carried out. Instead, an alternative procedure has been applied. Fracture mechanics specimens are considered as severely cracked components [1]. Pressure vessel parts can safely be used at the minimum design temperatures for such components. Pressure vessel parts can only have small defects to be put in operation. Such defects can remain undetected after manufacturing or be a result of fatigue in service. The assumed type of defects during design are semi-elliptical surface cracks with a depth of the fraction $\Theta(t)$ of the thickness t.

It is well known that there is a transition in the fracture behaviour around the temperature where the fracture toughness is 100 MPa√m. This temperature is designated T_{K100}. The toughness can be measured as the true fracture toughness K_{Ic} or as the elasto-plastic value K_{Jc}. When the temperature is falling below T_{K100} the failure is becoming increasingly more brittle. Above T_{K100} the failure is essentially ductile. This behaviour has also been observed for DSS [23], [24]. If the design temperature is above T_{K100} the risk for brittle failure is very limited.

In Figures 5 and 6 the design temperatures T_R are compared with T_{K100} values. T_R is plotted as a function of the impact transition temperature T_{27J}. If $T_R > T_{K100}$ the design procedure is conservative, if $T_R < T_{K100}$ the procedure is non-conservative. Results for 2304 are shown in Figure 5 and for 2205 and LDX 2201 in Figure 6. Since LDX 2101 and 2205 have about the same strength, they can be handled in the same diagram.

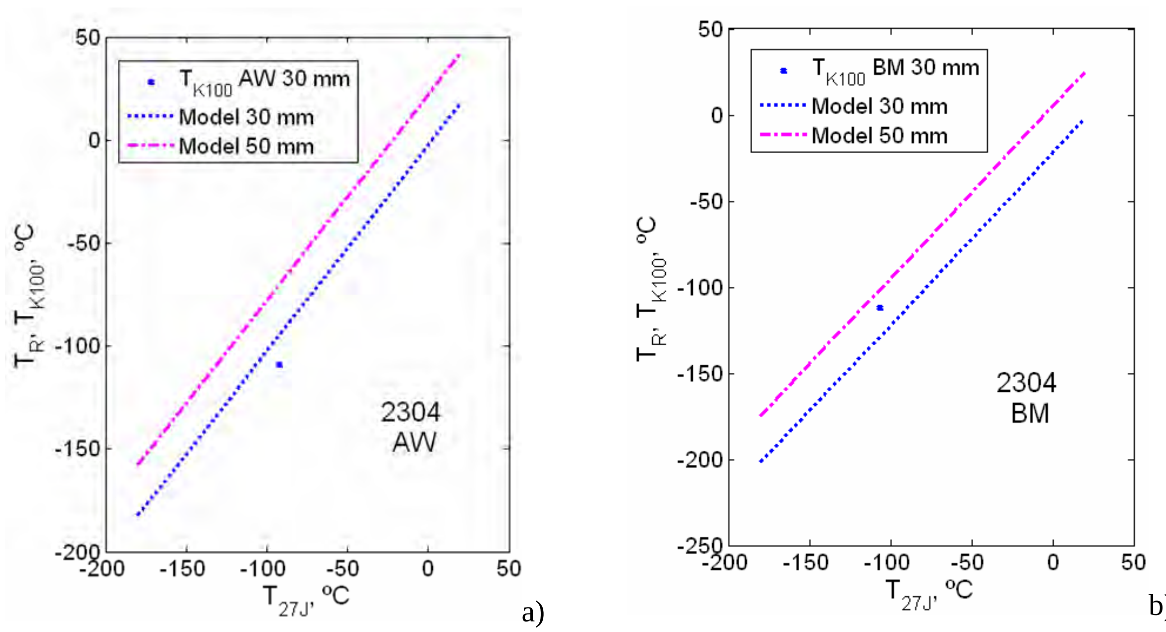

Figure 5. Measured T_{K100} and values for the minimum design reference temperature T_R as a function of the impact toughness specification temperature T_{27J}. T_{K100} is the temperature where the fracture toughness is K_{JC} = 100 MPa m. Specimen thickness 30 mm. The duplex stainless steel 2304. t_{50} = 10 mm. a) As-welded (AW) condition. b) Base metal (BM).

In Figures 5 and 6 each T_{K100} value has been determined by performing a series of fracture mechanics tests at different temperatures. These data are taken from [23] and [24]. Seven of the eight test series in Figures 5 and 6 give conservative results relative to the model.

The corresponding comparison has been made for the unalloyed high strength steels P420, P500 and P690. The number in the designation is the yield strength. In total, data for 40 test series of fracture toughness was available. All but six test series gave conservative results [1]. This demonstrates that the model is sufficiently conservative both for DSS and unalloyed steels.

It is evident from Figures 5 and 6 that the tested DSS have excellent toughness. This is demonstrated by the fact that T_{K100} was below -90 °C for all 8 test series. This implies that the steels can safely be used down to these low temperatures without risk for brittle failure. Further discussion of fracture toughness results for DSS can be found in [23], [24], [27]. It must be emphasized, however, that the microstructure must be closely controlled to obtain these excellent toughness values. Avoidance of sigma formation and sufficient austenite reformation are essential. Well adopted welding procedures are required, see e.g. [28], [29].

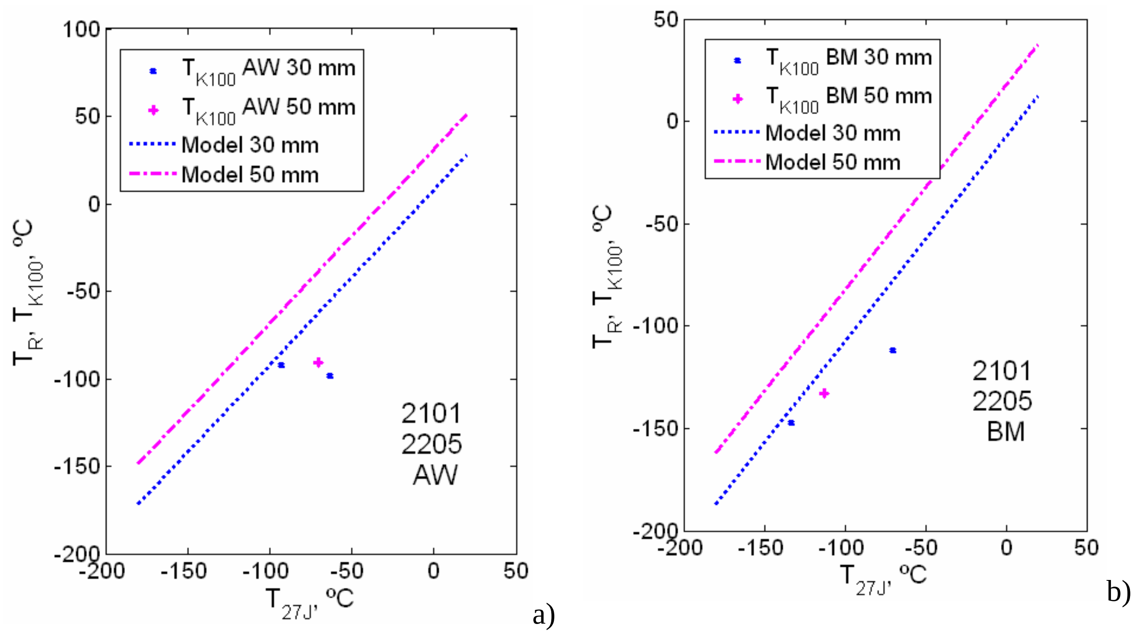

Figure 6. Measured T_{K100} and values for the minimum design reference temperature T_R as a function of the impact toughness specification temperature T_{27J}. Thicknesses 30 and 50 mm. The duplex stainless steels LDX 2101 and 2205. t_{50} = 10 mm. a) As-welded (AW) condition. b) Base metal (BM).

Neither the derivation of the model nor the tests that have been performed involve any specific assumption related to pressure vessels and the results should have general applicability also to other types of components. This implies that DSS can be applied down to low temperatures if suitable welding procedures are adopted.

Conclusions

A new model for design against brittle fracture is being implemented in the European pressure vessel code EN 13445.

- The code gives three alternative methods for the design against brittle failure for steels. Method 1 is a simple procedure where it is assumed that the design reference temperature is the same as the temperature where the impact toughness is specified in the harmonised EN material standard. The code gives a maximum allowed thickness for listed EN-materials for unalloyed and low alloyed steels. For austenitic stainless steels, conditions are given for impact toughness requirements.
- In Method 2 the minimum design temperature is provided for given thicknesses and test temperatures for the impact toughness test. The values are shown in monograms. Method 2 is now applicable to duplex stainless steels.
- Methods 1 and 2 are based on the same fundamental fracture mechanics model, and give the same results for identical cases. The choice of method is consequently a matter of convenience. The theoretical background to the model has been briefly summarised. Full details can be found in referenced papers. The design procedures have been verified experimentally for duplex stainless steels as well as for unalloyed and low alloyed steels up to 690 MPA strength.
- Method 3 is the most general method where basic fracture mechanics approaches can be applied freely. No specific procedure is given in the code. Expertise in the application of fracture mechanics and the design of pressure vessels is essential when using this method. Method 3 is primarily intended for cases where Method 1 or Method 2 is not applicable.

– The excellent toughness properties of parent metal and welds of the conventional duplex stainless steels LDX 2101, 2205 and 2304 allow them to be used down to low temperatures.

Acknowledgements

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NEW GRADE IN TKL-AST OF HIGH-NITROGEN AUSTENITIC STAINLESS STEELS (HNASS)

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Abstract

In this paper, the development of a new grade of structural austenitic stainless steel and its metallurgical background are reported. The new steel grade represents a valid alternative to conventional structural grades and to the 300-series, due to the low nickel content.
This grade has the same corrosion resistance of austenitic counterparts and it has elevated strength, with the focus on weight and cost reductions of the manufactured components. A number of applications within automotive sector and fire resisting structure are also proposed.

Introduction

Low-nickel, high-nitrogen and high-manganese austenitic stainless steels, containing chromium ranging between 16-18% mass, are very attractive due to their high mechanical properties and ductility, improved corrosion resistance and reduced tendency to grain boundary sensitization, and also for their low fabrication costs associated with nickel saving.
TKL-AST has developed a new grade of austenitic N-Mn stainless steel with a unique combination of mechanical strength, ductility (Figure1), compared to other structural steels, and, of course, elevated corrosion resistance. The approximated chemical analysis (% weight) is indicated as following:

C (%)	Cr (%)	Ni (%)	Mn (%)	N (%)	Cu (%)	Si (%)	Mo (%)
0.02÷0.10	15÷18	3.5÷4.5	up to 12	up to 0.3	up to 2	0.15÷0.60	up to 1

Generally speaking, the main features of this new grade are:

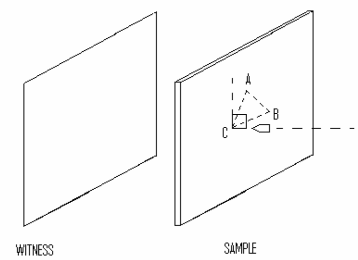
- High strength: Rp > 420 MPa; Rm > 750 MPa;
- Outstanding formability, especially when compared to the mechanical strength levels:
- Good weldability and corrosion resistance (substantially equivalent to AISI 304 / EN 1.4301); its cost is relatively moderate and stable due to reduced content or absence of expensive elements such as Ni or Mo;

Austenitic grades in general and in particular high Mn-N grades present high strain hardening coefficients. Mechanical characteristics increase therefore dramatically due to cold deformation, with a marginal decrease of formability. These properties provide the designers with a large freedom in that the material properties, due to cold rolling, are “customizable” in the most suitable way for the application, in a totally transparent way to the end user. Mechanical characteristics (as shown in Tab.2 with the summary of other physical properties) also depend on

the pre-strain state and on the strain rate value (i.e. the variation of the strain state as a function of time). Stainless steel grades, especially austenitic qualities, have a substantial advantage with respect to “light” alloys or carbon steel in terms of a greater sensitivity to strain rate. The greater the load application rate is the greater the material resistance will be with obvious performance benefits, especially in passive safety (crash) applications.
In this paper the main properties and suitable applications of this new grade are reported.

Experimental

Standard metallographic procedures were applied to prepare samples for optical microscopy as well as for scanning electron microscopical studies.
For the evaluation of mechanical properties, tensile tests were carried out according to ASTM E8 or UNI EN 10002-2 [2], using specimens 12.7 mm wide with a gage length of 80 mm. They were machined and deburred. The specimens were initially loaded at a strain rate ($\dot{\varepsilon}$) of 3mm/min in the elastic field, after which the strain rate was increased to 20 mm/min. Tensile tests were carried out on both annealed specimens, and on cold rolled specimens, reduced by a laboratory pilot plant with cold reduction comprised between 5% and 70%. The hardness of the new stainless steel was measured using a HB Brinell hardness tester with a load of about 980 N.
Low energy - impact behaviour of structural grades of stainless steel have been evaluated according to ASTM E23. The specimens sizes are 5 mm (o 2.5mm) x 10mm².



Impact test, for the evaluation of the ballistic behaviour, have been performed according to EN1063 standard that essentially prescribes speed and bullet type for the different qualification levels. Each sample (a 500 ±5mm square plate) must be hit by 3 bullets whose impact points must form the vertex of a 120 mm side equilateral triangle and not release spalls, upon impact, on a thin paper sheet (witness) positioned behind (see figure on the left).

Dynamic tensile tests (from $10^3\ s^{-1}$) have been performed on a split-Hopkinson bar apparatus. This test was carried out by means of a 5 meter, pneumatically accelerated, Hopkinson split bar, capable of a strain rate up to 1000 s^{-1}. Tests have been carried out on both annealed specimens and on 10% pre strained specimens, with different strain rates (1, 40, 80 and 200 s^{-1}).
Buckling stress vs temperature has been assessed through anisothermal transient state test carried out, according to EN 1993-1-2 standards, for temperatures between 200°C and 1200°C. Several H profiles, with the same geometry but made up of different materials have been compared.
The corrosion behaviour was evaluated by means of a potentiodynamic test according to ASTM G61. All potentials were measured against a saturated calomel electrode (SCE). Electrochemical studies were carried out in a glass chamber, with a thermostatic system. In order to ensure a good reproducibility of results (on the basis of ten curves), the solution (NaCl 35 g/l at room temperature) and the glass chamber were separately heated before the starting of each experiment and the surface of each sample was polarized at 1.1 mV/SCE for 90 s.
Potentiodynamic measurements were obtained at a scanning rate of 0.167 mV/s, using a Tacussel corrosion unit and a initial potential of -700 mV/SCE.

Metallurgical background

Nitrogen porosity

The solubility of nitrogen in the liquid steel is determined by the nitrogen Siewert’s law [1].

According to this, nitrogen gas bubbles result from segregation of this solute over the threshold limit of N concentration in the liquid, through the reaction:

$$N \text{ (solution)} \rightarrow \tfrac{1}{2} N_2 \text{ gas (in bubble)} \quad (1)$$

If supersaturation of this element is reached during solidification, gas bubbles can nucleate inside secondary interdendritic spaces (SDAS) [2], thus results in porosity of the final microstructure. There is an influence of chemical and process parameters on nitrogen bubble formation during solidification of high nitrogen austenitic stainless steel. Porosity formation in the solidification process can be reduced operating on two main factors:

- Steel composition (reduction of nitrogen activity in the residual melt);
- Solid growth rate (reduction of SDAS by means of an increase of the cooling rate).

From a theoretical point of view, processes with higher cooling rates, i.e. thin slab casting, strip casting could be reasonably used. In order to produce HNASS by conventional continous casting, adding elevated levels of Mn and Cr (the latter with a further positive effect on corrosion resistance) has been the adopted way.

Austenite stability

In low nickel, high nitrogen manganese stainless steels, in order to obtain a stable austenitic microstructure at room temperature, it is important to have a correct evaluation of the austenitic phase field stabilization that can be reached adding nitrogen and other elements commonly used to replace nickel such as carbon, manganese and, to a lesser extent, copper.
Among previsional models, Hull [4] adapted Schaeffler's diagram to high nitrogen alloyed stainless steels, solidified in rapid cooling conditions:

$$\begin{aligned} \mathrm{Nieq} &= \mathrm{Ni} + \mathrm{Co} + 0.1\mathrm{Mn} - 0.01(\mathrm{Mn})^2 + 18\mathrm{N} + 30\mathrm{C} \\ \mathrm{Creq} &= \mathrm{Cr} + 1.5\mathrm{Mo} + 1.5\mathrm{W} + 0.5\mathrm{Si} + 2.3\mathrm{V} + 1.75\mathrm{Nb} \end{aligned} \quad (2)$$

As can be seen in Eq. (2), manganese acts as an austenite stabiliser only for contents up to 10%. Copper is commonly considered a bland austenite stabilizer, having about half the effect of Ni. An excessive amount of delta ferrite leads to detrimental effects on the high temperature workability and corrosion resistance [5]. In Figure 2, it is possible to see an example of edge cracks on hot strip bands.
Thermocalc Software [6] can be useful in order to predict austenite stability as a function of chemical composition, and therefore in the choice of proper process conditions in order to avoid defects.
In Figure 3, the evolution of delta ferrite at hot rolling temperatures is reported. A low degree of austenite stability at roughing temperatures, leads to an high risk of crack formation. In the case of an intermediate stabilization of austenite, a reduction of slab reheating temperature is required to avoid crack formation, but it compromises the availability of low hot strip gauges. An elevated austenite stability allows to reheat the slabs at high temperature without risk of edges' defect formation.

Hot and cold rolling strip annealing and pickling

The influence of continuous annealing after hot rolling is important due to its effect on grain size. In order to achieve elevated mechanical properties, it is necessary to produce a fine grain structure after recrystallization, as proposed in Hall-Petch relation [3]:

$$\sigma_y = \sigma_0 + kD^{-1/2} \quad (3)$$

where:
σ_y : the yield stress;
σ_0 : the "friction stress"
k : the locking parameter
D : grain diameter.

After continuous annealing, the material was pickled with an ecological treatment. The result of a pickled surface and typical cold rolled austenitic microstructure is shown in Figure 4 (a, b).

Experimental results and evaluation of properties

Quasi-static and dynamic mechanical properties

Quasi-static mechanical properties showed higher yield strength and ultimate tensile strength of HNASS compared with typical austenitic stainless steel, but a lower forming capability and ductility as confirmed by elongation to rupture (see Table 1).
The work hardening behavior of HNASS is shown in Figure 5, where the materials show, at an intermediate level of cold deformation, an excellent combination of mechanical strength and ductility. A high capacity for crash energy adsorption due to its work hardening behaviour, was therefore expected.
In Figure 6 the results of dynamic tensile tests are reported.
Evaluation of materials' constitutive equations at high or very high strain rate (from $1s^{-1}$ to $100\ s^{-1}$) is nevertheless of significant importance with respect to several applications where deformation phenomena take place in very short laps of time: crash phenomena, ballistic, etc. Data reported in Figure 6 show that the strength levels are higher in work hardened material than annealed material. Oscillations increased with strain rate, as expected from Literature.
From the analysis of elongation to rupture, an increase of this property can be seen with strain rate, due to increasing of the sample temperature (adiabatic process).
The absorbed energy from -196°C to room temperature of the materials AISI 304 and HNASS is plotted in Figure 7. The figure shows that the absorbed energy decreases continuously with decreasing temperature. Data reported in Figure 7 shows that this material, as AISI 304, does not show DBTT temperature.
As for ballistic behavior, experimental tests showed for HNASS performance way superior to both martensitic and conventional austenitic test. Traditional martensitic grades, whose arresting properties are mainly due to energy absorption through fracture mechanics, modern high performance austenitic grades rely on different, more complex, mechanisms such as adiabatic shearing and others involving large strain at very high strain rate; the combination of yield strength and toughness appeared actually to be as the most influent characteristic.
Besides the higher yield stress (and strain hardening coefficient) of HNASS, with respect to conventional austenitic grades, proved to additionally enhance their ballistic behavior in comparison to the latter (Figure 8).

Corrosion properties (Pitting potential)

Corrosion resistance properties are comparable to 304, and in general superior to 200 series (Figure 9). As explained by PREN formulae, nitrogen has a beneficial effect on pitting corrosion resistance:

$$PREN = Cr + 3.3Mo + 16N \qquad (4)$$

HNASS has high level of corrosion resistance due to high nitrogen and chromium content. Despite its low nickel content, it can be considered a substitute of standard austenitic stainless steel, from a corrosion resistance point of view, when not extremely high ductility is required.

Applications

Fire resisting applications

This material can be used in fire resisting application, and its behaviour at temperature comprised between 200°C and 1200°C is described by buckling stress determined by anisothermal transient test, carried out according to EN 1993-1-2 (RFCS CR 04048) (Figure 10). HNASS behaviour at high temperatures is, especially for higher temperatures, definitely superior to structural carbon steel and, despite a Ni content of less than the half, closely comparable to that of EN 1.4541.

Automotive applications

The automotive sector can be regarded as strategic for commercial volumes (7.5% of global steel production is dedicated to the automotive sector). Development of new technologies, products, production processes, quality assurance, partnership build up, distribution, organization and logistic methods in the car industry are a reference for evolution of different market areas. Infact, automotive applications require:

- Stiffness increase of the structure while saving weight in order to improve dynamic performance;
- Performance increase in terms of passive safety or crashworthiness; this issue is also important in terms of quality perceived by end users;
- Weight saving in order to reduce fuel consumption and thus meeting antipollution standards (regulations aspect).

This feature can be exploited to improve automotive crashworthiness, defined as the capability of a car structure to provide adequate protection to its passengers from injury in the event of a crash, plays an important role in the design of passenger cars.
Comparison with alternative materials must keep into account the economic factor. Even if stainless steels are more expensive than common steels, they allow cost saving due to the life cycle cost of the structure.

Conclusions

The new steel grade developed belongs to the high N-Mn low nickel austenitic stainless steel. The chemical balancement assures a reliable process production without typical criticalities of this family (nitrogen bubbles, edge crack formation, difficult pickability).
Moreover, the material shows outstanding mechanical properties in different test conditions (both quasi static and dynamic strain rate, low and high temperatures).
The most suitable applications for this grade are lightweight structural applications (automotive) due to high specific energy absorption and fire resistance components.

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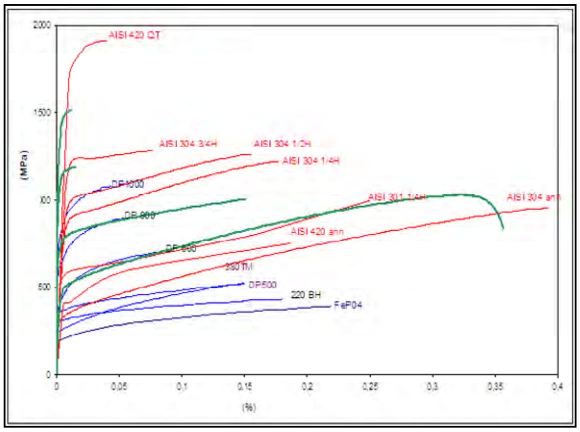

Figure 1. Mechanical strength and ductility of HNASS compared to other stainless steel grades

Figure 2. Edge crack on hot strip bands, due to high content of delta ferrite

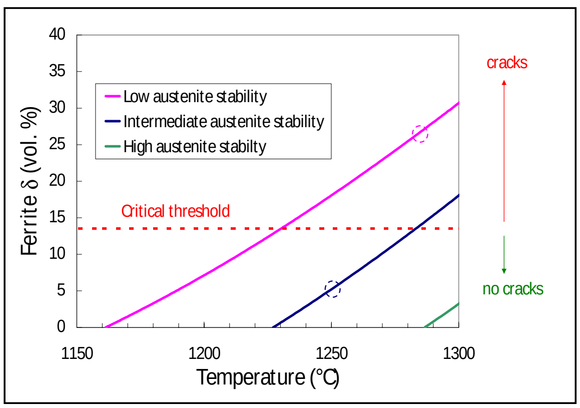

Figure 3. Evolution of delta ferrite content at hot rolling temperatures by ThermoCalc Software

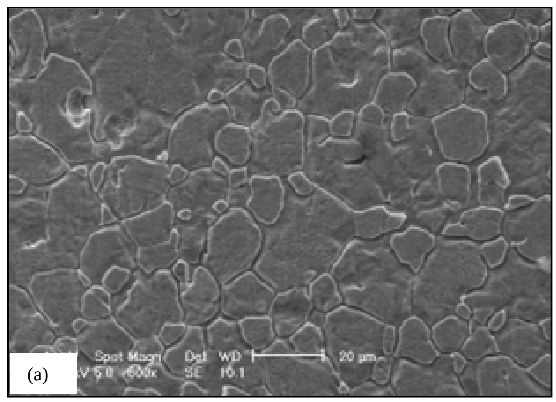

Figure 4 a). SEM micrograph of a cold pickled surface for HNASS

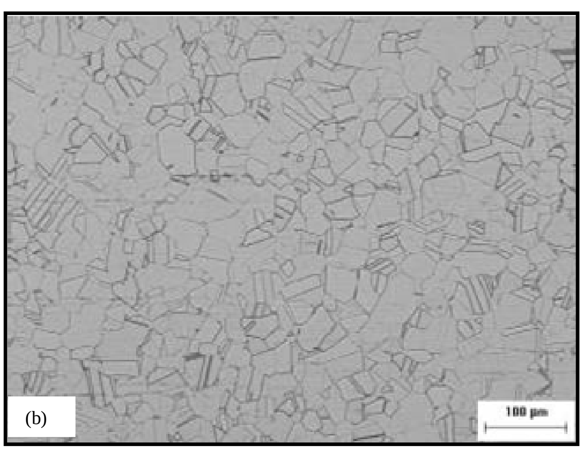

Figure 4 b). Typical austenitic microstructure of cold rolled strip for HNASS

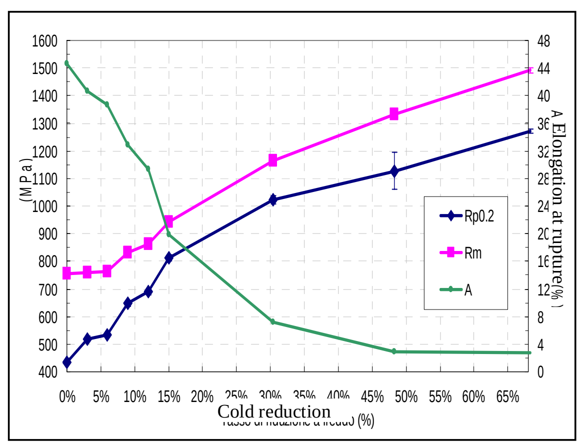

Fig. 5 The work hardening behaviour of AHNSS

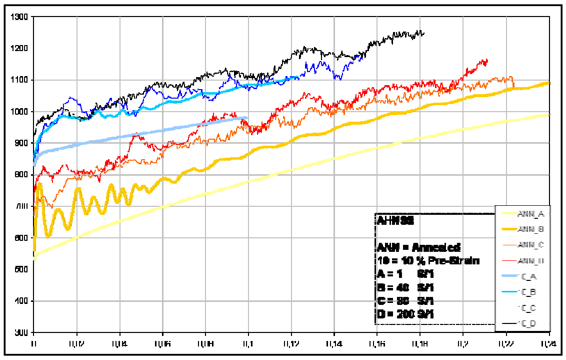

Figure 6. Dynamic tensile properties of HNASS

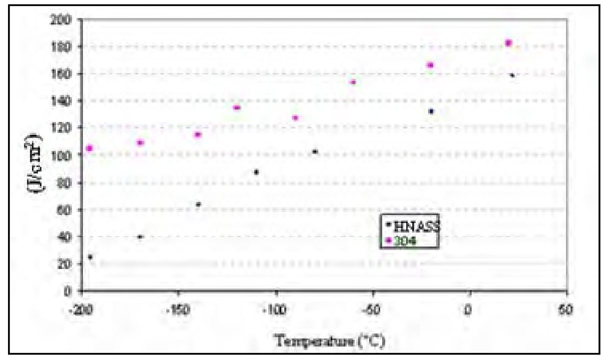

Figure 7. Charpy Impact energy of HNASS compared to 304 grade

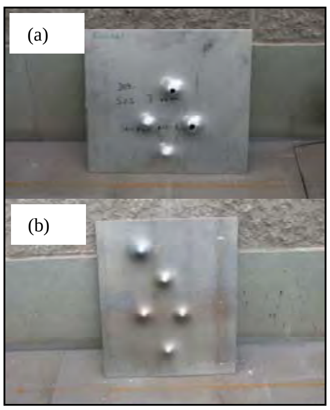

Figure 8. Samples of HNASS after ballistic test (b) according to EN1063 compared to 304 (a)

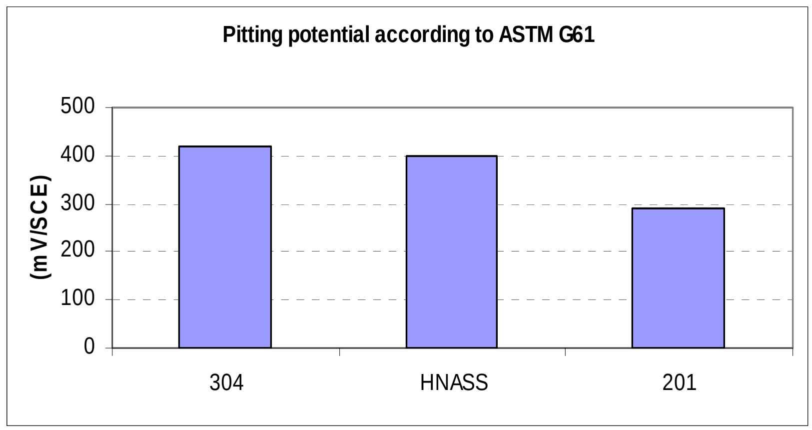

Figure 9. Corrosion resistance properties evaluated by pitting potential according to ASTM G61

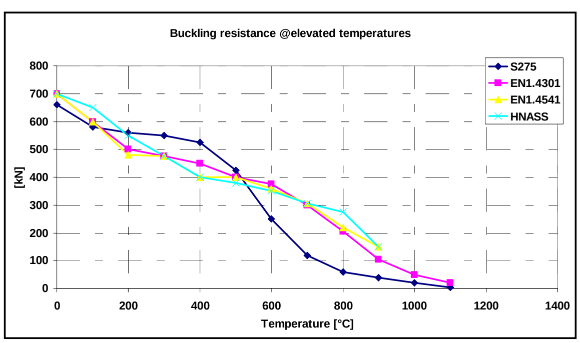

Figure 10. Buckling stress determined by anisothermal transient test according to EN 1993-1-2

	HNASS	304
A80 [%]	40-50	50-60
Rm [MPa]	700-800	600-670
Rp0.2 [MPa]	400-450	260-300
HRB	80-85	75-85

Table 1. Review of experimental mechanical properties of HNASS compared to typical 304 grade

A FIRE ENGINEERING APPROACH TO THE DESIGN OF STAINLESS STEEL STRUCTURAL SYSTEMS

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Abstract

The relatively sparse body of existing data on the behaviour of structural stainless steel at high temperatures suggests that stainless steel performs very well in certain circumstances due to its strength and stiffness retention characteristics at elevated temperatures. This paper gives an overview of the findings of a three year European research project which studied the behaviour of a range of structural stainless steel solutions subject to fire loading. The project included tests on materials, members and connections, numerical analysis and development of design guidance aligned to Eurocode 3: *Design of steel structures* and Eurocode 4: *Design of composite steel and concrete structures*. The performance of the stainless steel systems compared favourably with that of similar carbon steel systems at temperatures between 600ºC and 800ºC.

Introduction

All metals lose strength and stiffness when heated, though there is considerable variation in the rate of the degradation of mechanical properties between different metals. Austenitic stainless steels exhibit better strength retention than carbon steels above about 550ºC and better stiffness retention at all temperatures. The main reason for this is the difference in crystal structure of the two metals. The atoms in an austenitic microstructure are more closely packed than in carbon steels, which have a ferritic microstructure. Austenitic stainless steels have a relatively high level of alloying elements compared to carbon steels. Alloying additions tend to lower the diffusion rates of atoms within the crystal lattice at a given temperature which slows down the softening, recrystallisation and creep deformation mechanisms which control strength and plasticity at elevated temperatures. Additionally, carbon steels undergo transformation from ferrite to leanly alloyed austenite on heating. The austenitic steels, in contrast, do not undergo a structure change in the range of temperatures relevant to fire resistant design.

As a result of the superior strength and stiffness retention, stainless steel columns and beams generally retain their load-bearing capacity for a longer time than equivalent carbon steel columns. A conservative approach to fire resistant design of stainless steel structures is covered in an informative annex to EN 1993-1-2[1], despite fire test data on stainless steel structural members being sparse. In an attempt to develop more comprehensive and economic design guidance, the Stainless Steel in Fire project started in 2004, funded by the European Research Fund for Coal and Steel (RFCS) and stainless steel producers. The final report of the project will be presented to the RFCS in 2008[2]. SCI co-ordinated this project and the partners were CTICM, CSM, Outokumpu Stainless, Univeristy of Hannover, VTT, SBI and ArcelorMittal Stainless. Stainless steel in buildings is almost always exposed, so the Stainless Steel in Fire project aimed to identify structural solutions which give a specified period of fire resistance without any fire protection applied to the surface of the steel. Benefits of eliminating fire protection include lower construction costs, shorter construction time, more effective use of the internal floor area and more attractive appearance. The project included tests on materials, members and connections, numerical analysis and development of design guidance aligned to European design standards. The scope of the work was limited to austenitic grades as these exhibit the most promising behaviour at high temperature. The topics studied were:

- Load-bearing and separating elements with 30 and 60 minutes fire resistance
- Concrete filled hollow sections in fire
- Hybrid stainless-carbon steel composite floor beams in fire
- Slender hollow sections in fire
- Strength and stiffness retention of grades not previously studied
- Welded and bolted connections in fire
- Behaviour of external stainless steel columns and stainless steel columns in open car parks subject to realistic fire loads

Mechanical properties of stainless steel at elevated temperatures

Strength and stiffness retention factors have been derived from isothermal and anisothermal test data for a number of grades of stainless steel used in structural applications[3]. It is generally accepted that the results of isothermal tests are only accurate up to temperatures of about 400ºC; above this temperature they give unconservatively high results and data from anisothermal tests should be used which more closely replicate a real fire situation. Figure 1 shows the 0.2% proof strength retention curves for a number of grades, including two grades in the work hardened condition C850.

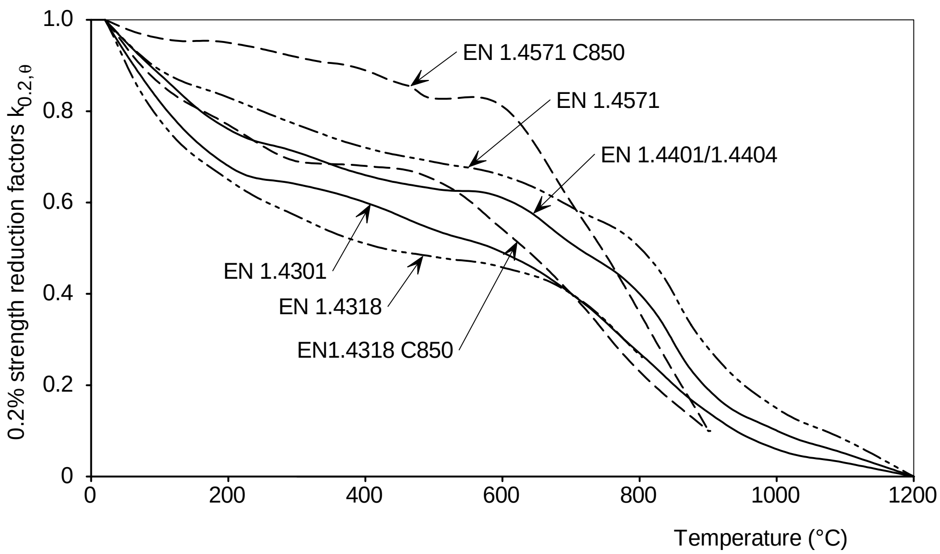


Figure 1. 0.2% proof strength retention curves for austenitic structural stainless steels

Having a unique set of reduction factors for each different grade is awkward for designers and unjustified due to the high scatter in the test data. Bearing in mind that carbon steels are currently described in EN 1993-1-2 by one set of strength retention curves, work is underway rationalising the stainless steel curves into a smaller number of generic curves. It is proposed that the following five generic curves are developed:

- Chromium-nickel austenitic grades (e.g. 1.4301)
- Chromium-nickel-molybdenum austenitic grades (e.g. 1.4401)
- Stabilised austenitic grades (e.g. 1.4571)

- Ferritic grades (e.g. 1.4003)
- Duplex grades (e.g. 1.4462)

Stainless steel columns in fire

The structural performance of a stainless steel rectangular hollow section (RHS) column (200x200x8) from grade 1.4301 was compared to the performance of an identical carbon steel column from grade S235 at different temperatures using finite element analysis (Figure 2). For a cross-sectional temperature of 400°C, the stainless and carbon steel columns showed similar load-bearing capacity. At 600°C, the stainless steel columns exhibited much higher load-bearing capacity than the carbon steel columns; the ratio of ultimate loads of the stainless to the carbon steel column is about 2.0. The explanation for this is that the good stiffness retention results in the non-dimensional slenderness of the column tending to reduce as the temperature increases. This improves the flexural buckling behaviour of the column leading to smaller lateral deflections and reducing second order effects. For temperatures between 600°C and 800°C, the ratio of stainless to carbon steel ultimate load rises significantly, clearly demonstrating that stainless steel columns show superior load-bearing behaviour to carbon steel columns in this temperature range.

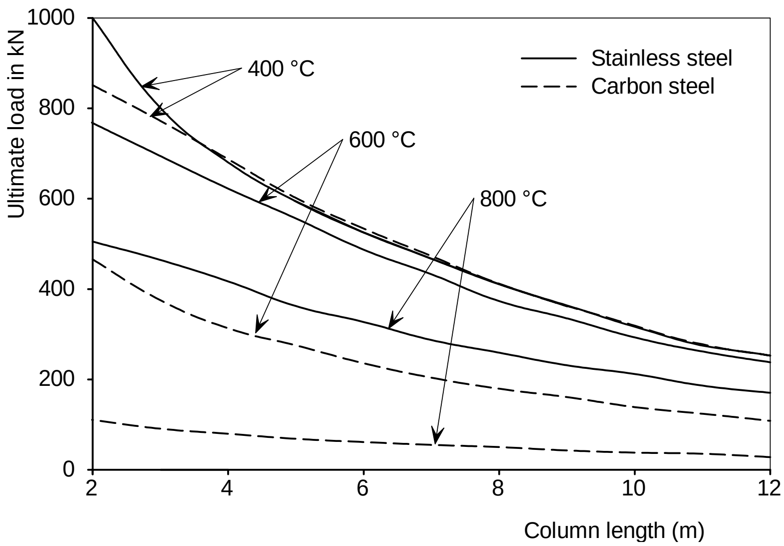


Figure 2. Ultimate loads for varying column length and cross-sectional temperatures

Limiting the temperature rise will enable the load-bearing capacity of a member to be retained for a longer period. In the Stainless Steel in Fire project, the temperature development in a range of concepts designed to suppress temperature rise was studied. Using finite element analysis, the EN 1363-1[4] standard fire curve was applied for 60 minutes to a range of systems including:

- concentric tubes (with the annulus between the sections either empty, filled with mineral wool or filled with concrete),
- a corner column section partially protected by concrete walls,
- a column exposed to fire from one side,
- two profiles side by side filled with mineral wool.

Unloaded fire tests on the most promising concepts were then carried out. The temperature development measured in the tests agreed reasonably well with the temperatures predicted by numerical analysis. After 60 minutes, the temperature of the outer RHS in the concentric tube concept had reached 925°C whereas the temperature of the inner section was only 414°C, which meant that the inner tube retained about 60% of its load-bearing capacity according to EN 1993-1-2. For the corner column concept, the maximum temperature in the exposed corner was 806°C whereas the unexposed corner only reached 299°C. Design guidance which takes into account non-uniform temperature distribution of a member subject to flexural buckling needs to be developed to take advantage of the protection offered by concrete walls to corner columns.

A programme of tests on RHS with slender (Class 4) cross-sections was also performed in the project (Figure 3). Numerical models were calibrated against test results and then parametric studies carried out to develop more economic design guidance for Class 4 RHS than is currently in existing guidance[1,3].

Figure 3. Tests on RHS with slender cross-sections
Left: Test specimen in furnace, *Right*: Test specimens after fire tests (RHS 150x150x3)

Composite stainless steel-concrete columns in fire

Fire tests were carried out on seven RHS columns filled with concrete (reinforced and unreinforced). The specimens were designed to achieve a fire rating of 30 and 60 minutes and were made from grade 1.4404 stainless steel. The columns were subjected to an eccentrically applied compressive load and exposed to controlled heating following the EN 1363-1 standard fire curve. The specimens were pinned at both ends, which were free to rotate about one direction but were restrained to rotate about the perpendicular direction. The measured failure times exceeded the expected fire ratings in all cases.

The tests were modelled numerically using the advanced finite element model SISMEF to simulate the mechanical behaviour and resistance of composite members exposed to fire. Subsequently, parametric studies were carried out in order to develop design rules for composite columns. The proposed design methods are consistent with the general flow charts in EN 1994-1-2[5] used to check the fire resistance of composite members but include some specific characteristics to account for the distinctive behaviour of stainless steel.

To compare the performance of stainless and carbon steel composite columns, a numerical study was carried out on three different RHS column cross-sections filled with unreinforced concrete; the results are given in Table 1. It is clear that carbon steel columns buckle at a lower load than stainless steel columns of identical size and length. For a given fire rating, maximum load level of stainless steel columns increases with increasing cross-section size. This is mainly due to the lower temperature rise of the large cross-section in comparison to the smaller cross-section.

Table 1. Comparison of maximum load level for concrete filled RHS columns (length = 3 m)

Column	Fire rating (minutes)	Maximum load level[1)]	
		Stainless steel column (grade 1.4401)	Carbon steel column (grade S235)
150x150x8	30	0.36	0.15
	60	0.16	0.04
200x200x8	30	0.36	0.15
	60	0.16	0.06
300x300x8	30	0.65	0.47
	60	0.29	0.15

[1)] The load level is the ratio of the buckling resistance at the fire ultimate state to the buckling resistance at room temperature

Composite carbon steel-stainless steel-concrete beams in fire

Under the Stainless Steel in Fire project, two fire tests were carried out on 'Slimflor' composite beams from grade 1.4404 with the stainless steel lower flange exposed and the carbon steel section unexposed (Figure 4). The specimens were 5 m in length and designed to achieve a fire rating of 30 and 60 minutes. As with the composite columns, the measured failure times exceeded the expected fire ratings in all cases. The tests were modelled numerically using the advanced finite element model SISMEF. Subsequently, parametric studies were carried out in order to develop design rules for composite beams. The proposed design method is based on simple plastic moment theory, requiring the calculation of the neutral axis and corresponding moment resistance by taking into account the temperature distribution through the cross-section and the corresponding reduction in material strength.

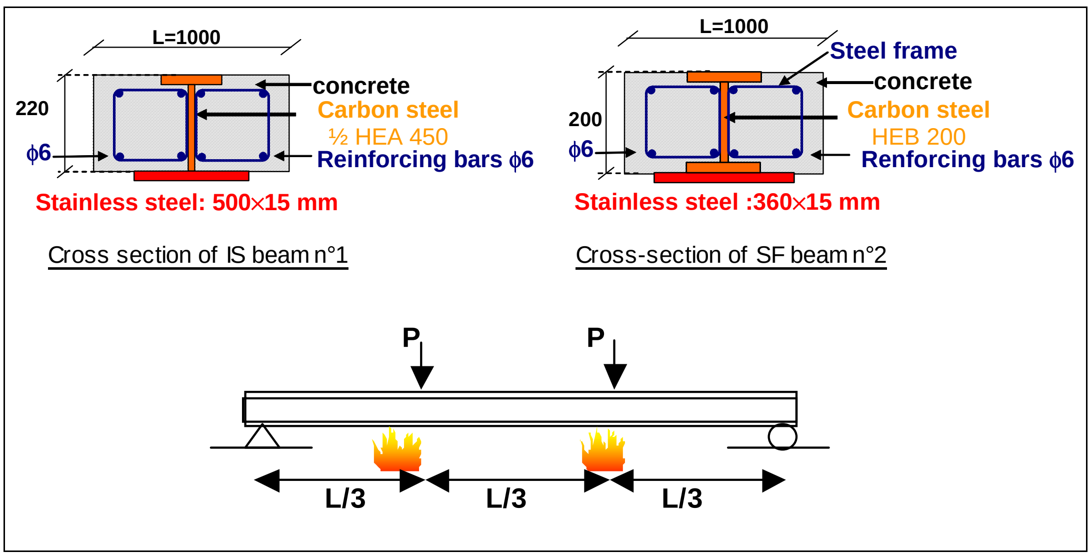
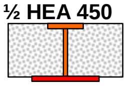
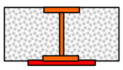


Figure 4. Structural details of the composite beam test specimens

To compare the performance of stainless and carbon steel composite beams, a numerical study was carried out on different beam cross-sections; some results are given in Table 2. For the same fire rating, the bending moment resistance of carbon steel beams is always lower than the beam with the exposed lower flange from stainless steel. 120 minutes fire resistance can easily be achieved by the ½ HEA 450 beam with exposed stainless steel plate providing the load level is lower than 0.33. In contrast to this, the carbon steel beam only achieved a fire resistance of 60 minutes with a load level of 0.27.

Table 1. Comparison of maximum load level for beams with exposed carbon steel and stainless steel plates

Beam	Fire rating	Maximum load level[1)]	
		Stainless steel lower plate (grade 1.4401)	Carbon steel lower plate (grade S235)
½ HEA 450  **Steel plate: 500×15 mm**	R60	0.72	0.27
	R90	0.46	0.17
	R120	0.33	0.15
HEB 280  **Steel plate: 480×20 mm**	R60	0.92	0.55
	R90	0.77	0.28
	R120	0.58	0.22

[1)] The load level is the ratio of the moment resistance at the fire ultimate state to the moment resistance at room temperature

Conclusions

The European Stainless Steel in Fire project has enabled a better understanding of the heating up characteristics and degradation of resistance of stainless steel members in a fire to be studied both through fire tests and numerical modelling. The work has shown that stainless steel structural members exhibit better fire resistance than carbon steel structural members in the temperature range 600ºC to 800ºC. Design guidance aligned to EN 1993-1-2 and EN 1994-1-2 was developed for the structural members studied.

Acknowledgement

The work described in this paper was carried out with a financial grant from the Research Fund for Coal and Steel of the European Community (Project RFS-CR-04048).

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NEW DESIGN TOOLS FOR STRUCTURAL HOLLOW SECTIONS OF STAINLESS STEEL

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Abstract

Previously stainless steel has been used in buildings as facades, envelopes, canopies, roofing and water drainage systems mainly for aesthetic reasons. The design standards and manuals for stainless steel structural members and connections in Europe have been developed since the beginning of the 1990's. Those standards and manuals give recommendations on how to select the most appropriate grade of stainless steel for a given application and provide information on the mechanical properties, physical properties and design strength. Until recently, in many applications stainless steel structural hollow sections were taking a share as structural elements covering square, rectangular and circular cross-sections. Therefore, research has been conducted on members and welded connections in hollow sections by testing structural resistances at room temperature and in fire situations.

In this paper new design tools are presented in order to help designers to utilise stainless steel structural hollow sections. Information in this field developed in Europe, Australia and North America by different R&D projects was included in the Design Handbook. This Design Handbook covers aspects of material behaviour, cross-section design, member design, connections, fire resistant design, fabrication and design examples. The Design Handbook gives profound information and recommendations for designers who already are familiar with carbon steel structural hollow sections.

In addition, the software WinRami Stainless was developed and modified to include structural calculation of stainless steel structural hollow sections. WinRami Stainless is the FE-based structural design software, which includes the resistance calculation based on the standard EN 1993-1-4: Eurocode 3- Design of steel structures – Part 1-4: General rules – Supplementary rules for stainless steels[1] and the standard EN 1993-1-2 Eurocode 3: Design of steel structures - Part 1-2: General rules - Structural fire design[2]. Materials included are the austenitic grades given in the Annex C of EN 1993-1-2 and in Table 7.1 of the Third Edition of the Design Manual for Structural Stainless Steel [5]. The material models used are based on Eurocode 3. Structural design with WinRami Stainless software utilizes two strength classes for structural hollow sections: annealed condition stainless steel grades and cold worked grade CP 350 and C700. For fire resistant design the reduction factors calculating strength and elastic modulus at specific temperature are given according to EN1993-1-2. WinRami Stainless is used for solving 2D structures consisting of frames and trusses.

Introduction

Stainless steel structural hollow sections have great potential in structural applications in all the branches of industry. These profiles are very well known and used in industrial applications in which good corrosion resistance is needed. Many research projects has been performed to determine the resistance of columns, beams and joints exploiting the enhancement in mechanical strength as a result of cold-working. The structural testing results of RFCS-funded research projects of stainless steels [3,4] are included in Eurocode standards. The structural hollow sections have also been studied outside Europe since the beginning of the 1990's [9,10,11]. The enhanced strength of cold-worked hollow sections of austenitic grades has been studied for a yield strength of appr. 450 N/mm^2 in welded structures [6,12,13,14]. The Steel Construction Institute (SCI) has developed software[3,4] suitable for calculating the resistance of a single member based on EN1993-1-4. The latest results of RFCS projects were published by SCI and Euro-Inox in the Third Edition of the - Design Manual for Structural Stainless Steel, published in 2006[5].

This paper is focused on mechanical strength of stainless steel hollow sections, though many other items are also discussed in the Design Handbook for structural hollow sections of stainless steel. The main differences from structural steel properties are the strong ability for strain hardening within the austenitic grades, high mechanical strength at short term higher temperatures and corrosion resistance. The Design Handbook for structural hollow sections of stainless steel and WinRami Stainless have been developed based on the standard EN 1993-1-4, Finnish national annex NA and related standards EN 1993-1-1, EN 1993-1-8 and EN 1993-1-2. The material selection from a corrosion point of view is shown according to EN 1993-1-4 and the Material Handbook [15] (in Finnish).

Design Handbook for structural hollow sections of stainless steel

The Design Handbook follows the recommendations for structural design with hollow sections given by EN 1993-1-4. The standard EN 1993-1-4 allows the strength to be utilised up to a yield strength value of 480 N/mm^2. EN 1993-1-4 ANNEX B B.2 (2) says "The design rules given in this Part 1-4 are applicable for materials up to grade C700 and CP350".
Austenitic grades (1.4301, 1.4401/1.4404, 1.4541 and 1.4571) and ferritic grades (1.4003, 1.4509 and 1.4521) in the annealed condition have a yield strength between 220 - 320 N/mm^2 (exception austenitic grades 1.4318 and 1.4372, f_y = 350 N/mm^2). The yield strength enhanced by cold-working is allowed to be used as nominal yield strength in context with austenitic grades. The nominal strength of cold-formed hollow sections is classified to a strength class of CP350 and C700. It is possible to utilise a higher strength class than CP350 and C700 for cold-formed hollow sections with the procedure given in EN 1993-1-4. The duplex-grades 1.4462 and 1.4162 have a yield strength value of 480 N/mm^2 which is used as nominal yield strength.

The Design Manual [5] allows the strength achieved by cold-working to be utilised at maximum CP500. In addition, in the guidance on fire resistance the Design Manual presents a less conservative approach than EN 1993-1-4.

The austenitic stainless steel grades have high mechanical strength values for a short period at high temperatures. The yield strength and modulus of elasticity sustains their values well up to temperatures of 800 ^{0}C. Figure 1 shows the value of effective yield strength for fire design with three different austenitic stainless steel grades.

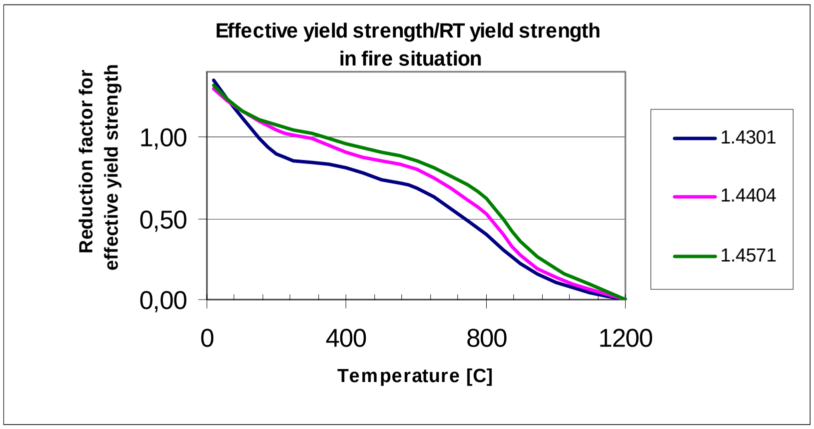


Figure 1. Reduction factors as a function of temperature for effective yield strength of austenitic grades 1.4301, 1.4404 and 1.4571.

The effective yield strength $f_{y,\theta}$ is calculated using the formula given below (EN 1993-1-2):

$$f_{y,\theta} = f_{0,2p,\theta} + k_{2\%,\theta}(f_{u,\theta} - f_{0,2p,\theta}) \qquad (1)$$

The parameter values for formula (1) are given by standard EN1993-1-2. The Design Manual [5] gives the parameter values for the materials in strength class CP500.

Table 1. Stainless steel grades used as hollow section material.

	Steel	Typical chemical alloying, %						$R_{p0,2}$ [N/mm^2]	R_m [N/mm^2]	A_5 [%]	KV [J]
	EN [1)]	C	N	Cr	Ni	Mo	Muut	RT	RT	RT	RT
Ferritic stainless steel	**1.4003**	0,02	-	11,2	0,5	-	-	320	450	20	-
	1.4509	0,02	-	18,0	-	-	Ti+Nb	250	430	18	-
	1.4512	0,03	-	11	-	-	Ti	220	380	25	-
	1.4521	0,02	-	18	-	2	Ti+Nb	320	420	20	-
Duplex-stainless steel	1.4162	0,03	0,22	21,5	1,5	0,3	5Mn	450	650	30	60
	1.4362	0,02	0,10	23	4,8	0,3	-	400	630	25	60
	1.4462	0,02	0,17	22	5,7	3,1	-	460	640	25	60
	1.4410	0,02	0,27	25	7	4	-	530	730	20	60
CrNi- ja CrMn-stainless steel	**1.4318**	0,02	0,14	17,7	6,5	-	-	350	650	40	60
	1.4372	0,05	0,15	17	5	-	6,5Mn	330	750	40	60
	1.4301	0,04	-	18,1	8,3	-	-	210	520	45	60
	1.4307	0,02	-	18,1	8,3	-	-	200	500	45	60
	1.4311	0,02	0,14	18,5	10,5	-	-	270	550	40	60
	1.4541	0,04	-	17,3	9,1	-	Ti	200	500	40	60
	1.4306	0,02	-	18,2	10,1	-	-	200	500	45	60
CrNiMo –stainless steel	**1.4401**	0,04	-	17,2	10,2	2,1	-	220	520	45	60
	1.4404	0,02	-	17,2	10,1	2,1	-	220	520	45	60
	1.4436	0,04	-	16,9	10,7	2,6	-	220	530	40	60
	1.4432	0,02	-	16,9	10,7	2,6	-	220	520	45	60
	1.4406	0,02	0,14	17,2	10,3	2,1	-	280	580	40	60
	1.4571	0,04	-	16,8	10,9	2,1	Ti	220	520	40	60
	1.4435	0,02	-	17,3	12,6	2,6	-	220	520	45	60
	1.4539	0,01	-	20	25	4,3	1,5Cu	220	520	35	60
	1.4529	0,02	0,2	20	25	6,5	0,5Cu	300	650	40	60
	1.4547	0,01	0,2	20	18	6,1	Cu	300	650	40	60
	1.4565	0,02	0,45	24	17	4,5	5,5Mn	420	800	30	90

[1)] Stainless steels with bold marking are included in EN 1993-1-4.

The Design Handbook presents the mechanical properties of hollow sections, Table 1, in structural applications highlighting the different stainless steel grades and their alloying from the point of view of corrosion properties, material choice for given boundary conditions and handling as well as fabrication in workshops. Information given in the Design Handbook covers widely used austenitic and duplex stainless steel grades. Ferritic-, austenitic CrMn- and lean-duplex grades are also included.

WinRami Stainless

The WinRami software has been developed for the strength calculation of lattice truss and frame structures made of structural hollow sections or welded I-profiles. The software is capable of solving displacement, member forces and support reactions of a structure. The structural analysis is based on FE-calculation. Loading can act as in-plane load and the structural analysis done is 2D-analysis. The resistance analysis is capable of taking care of buckling of members both in-plane and out-of-plane directions. Initially the WinRami software was developed by Rautaruukki Oyj for carbon steel structural hollow sections and the resistance analysis for stainless steel structures has been added to the software later.

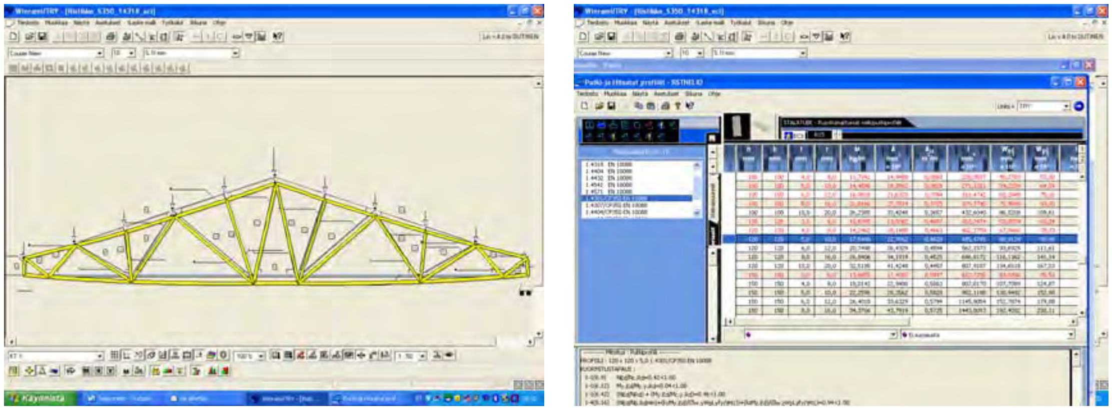


Figure 2. A schematic view of WinRami stainless resistance analysis.

The resistance analysis is based on the chosen design code for structural hollow sections of rectangular, square and circular cross section. The design code for stainless steel structural hollow sections is based on EN1993-1-4 and Finnish national annex, which refers to EN 1993-1-1, EN1993-1-2 and EN1993-1-8. The Winrami software includes the programs PROFILE, LIICONT and MOMCONT. The PROFILE is capable of solving a single member resistance. LIICON and MOMCON are programs solving the lattice girder joints and beam-to-column joints.

Main differences from structural steel hollow section resistance analysis are the values of partial factors, strength classification of cold-worked material, buckling curve, interaction of bending moment-normal force, and material mechanical strength at fire temperatures. The main differences are explained below.

The partial factors used by WinRami Stainless are recommended values according to EN 1993-1-4.

Winrami-stainless includes the structural and resistance analysis at room temperature and at fire situation temperatures for austenitic materials 1.4301, 1.4307, 1.4318, 1.4404, 1.4432, 1.4541 and 1.4571. Austenitic grades were chosen because of their good availability in a wide dimension range as structural square-, rectangular- and circular hollow sections. The maximum nominal design strength value in software for austenitic grades of cold-worked hollow sections is 350 N/mm^2 which conforms to strength class C350 and C700.

The buckling curve for stainless steel hollow sections is different from structural steel one by the value of limiting slenderness (0,2 to 0,4 stainless steel) and by the value of the modulus of elasticity E (210000N/mm^2 to 200 000 N/mm^2 stainless steel). The buckling curve “c” is used for stainless steel cold formed hollow sections.

Interaction normal force-bending moment at room temperature design differs from that of structural steels when calculating the interaction factors k_y and k_z. WinRami stainless uses the recommended formulae for determining the value for interaction factors.
When the loading is axial compression and uniaxial major axis moment the failure mode is buckling about the major axis:

$$\frac{N_{\mathrm{Ed}}}{(N_{\mathrm{b,Rd}})_{\min}} + k_y \left(\frac{M_{\mathrm{y,Ed}} + N_{\mathrm{Ed}}\, e_{\mathrm{Ny}}}{\beta_{\mathrm{W,y}} W_{\mathrm{pl,y}}\, f_{\mathrm{y}} / \gamma_{\mathrm{M1}}} \right) \leq 1 \qquad (2a)$$

When the loading is axial compression and uniaxial minor axis moment the failure mode is buckling about the minor axis:

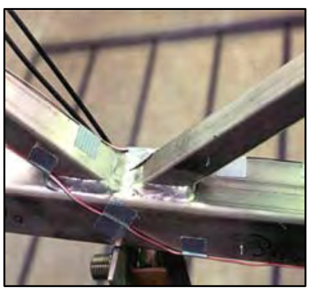
$$\frac{N_{\mathrm{Ed}}}{(N_{\mathrm{b,Rd}})_{\min}} + k_z \left(\frac{M_{\mathrm{z,Ed}} + N_{\mathrm{Ed}}\, e_{\mathrm{Nz}}}{\beta_{\mathrm{W,z}} W_{\mathrm{pl,z}}\, f_{\mathrm{y}} / \gamma_{\mathrm{M1}}} \right) \leq 1 \qquad (2b)$$

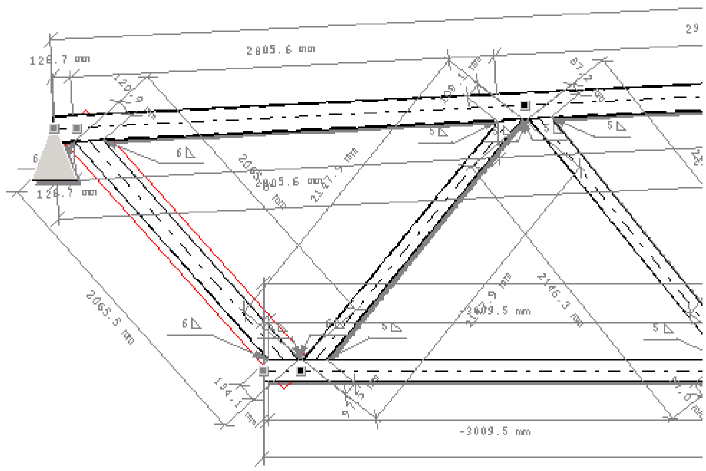
The interaction factors are calculated as follows:

$$k_y = 1{,}0 + 2\left(\bar{\lambda}_y - 0{,}5\right)\frac{N_{Ed}}{N_{b,Rd,y}} \text{, but } 1{,}2 \leq k_y \leq 1{,}2 + 2\frac{N_{Ed}}{N_{b,Rd,y}} \qquad (2.1)$$

$$k_z = 1{,}0 + 2\left(\bar{\lambda}_z - 0{,}5\right)\frac{N_{Ed}}{\left(N_{b,Rd}\right)_{\min 1}} \text{, but } 1{,}2 \leq k_z \leq 1{,}2 + 2\frac{N_{Ed}}{\left(N_{b,Rd}\right)_{\min 1}} \qquad (2.2)$$

Lattice girder joints are calculated according to ENV 1993-1-8. The calculation includes checking of the geometry of joints and structural resistance of joints. This means tens of formulae to be checked, Table 3. The yield strength of the profiles is restricted to a maximum of 460 N/mm^2 by ENV 1993-1-8. WinRami stainless includes materials whose maximum yield strength is limited to 350 N/mm^2. The typical stainless materials which reach 460 N/mm^2 are duplex- and cold-worked (CP500) austenitic grades, but are excluded from existing the WinRami stainless version in the current situation.





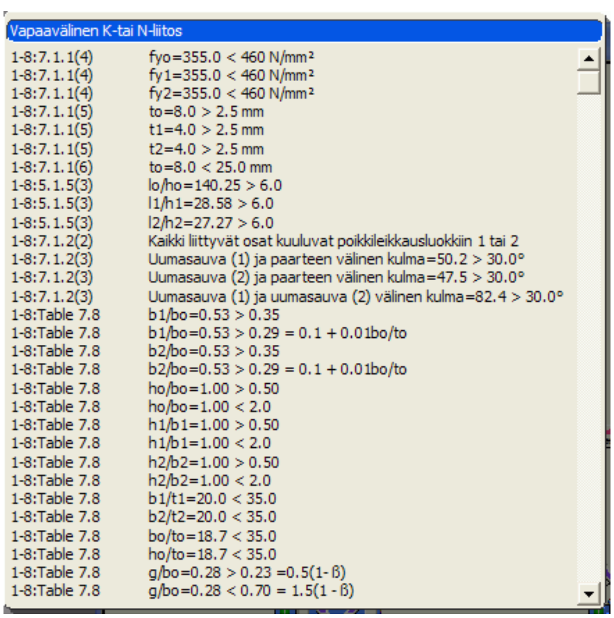


Figure 3. View of WinRami stainless joint calculation.

The calculation of the temperature rise of stainless steel differs slightly from that of carbon steel. The parameters are given by EN 1993-1-2. The emission factor value used is 0.4. WinRami stainless has an option to use a value of 0,2 [7,8].

Conclusions

New design tools to utilise stainless steel structural hollow sections in applications have been summarised including the Design Handbook and the software WinRami Stainless. The Design Handbook includes information about material grades, corrosion resistance, mechanical strength, structural resistance and work shop fabrication. The Design Handbook is targeted for detailed information about structural hollow sections of stainless steel. The WinRami Stainless is structural calculation software for truss and frame structures made of stainless steel. The WinRami Stainless is capable of solving the structural resistance of a structure based on EN1993-1-4 and related standards at room temperature and a fire situation. The Winrami Stainless software is targeted for the daily use of structural engineers.

Further development of design tools

The Design Handbook for structural stainless steel of hollow sections should be targeted to publish material information for structural purposes; such as material properties, design rules and design details. The Design Handbook shall be developed and dated parallel with design code development and practises in daily engineering work.

The further development of WinRami Stainless should be targeted to follow the changes in design codes and include the changes into the software. The other target is to include other suitable stainless steel grades like duplex-, lean duplex-, ferritic- and CrMn grades into software.

Acknowledgment

The new design tools for structural hollow sections of stainless steel presented in this paper have been generated as a result of the projects in cooperation with Stalatube Oy, Outokumpu Stainless Tubular Products (OSTP), the Finnish Constructional Steelwork Association (FCSA) and Outokumpu Tornio Works.

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STAINLESS STEELS AND THE WATER INDUSTRY: FROM KNOWLEDGE TO APPLICATIONS

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Abstract

There is increasing pressure to provide more clean drinking water to more people. At the same time, impact on the environment must be minimized. Stainless steels can and do play an important part in providing cost-effective solutions to these requirements. However, this can only happen when the relevant properties and costs are understood by those who have to make the choice of material for a particular application.

This paper describes how knowledge of corrosion resistance of stainless steels translates into standards and approvals for drinking water contact. It then considers how the properties of stainless steels can be used to advantage when designing durable, cost-effective equipment. This information has to be presented to design engineers and manufacturers locally if they are to consider using stainless steel. Examples will be given of the approaches taken in different countries to increase the market, which might find wider applicability.

One of the most persuasive factors is practical experience. Case studies from Europe, America and Australasia show the reasons behind the choice of stainless steel for applications in water treatment plants, distribution and storage systems, and plumbing in both prestigious and high-rise buildings. Examples are also given of recent innovations.

Taken together, this knowledge from other parts of the world may be used to advantage in local markets.

Introduction

Clean drinking water is a precious resource which many of us take for granted. However, there is increasing pressure to provide more of it to more people throughout the world. There is also a growing awareness of the need to reduce our impact on the environment. That has been particularly apparent in the last few years with wider debate of climate change and sustainability. We know that stainless steels can help to meet these two challenges but we need to convince designers, fabricators and operators in the water industry. That is where the link is needed between Science and Market.

We are very familiar with the properties of stainless steels but we need to present them from the user's point of view. From that perspective, what is required from a material for use in equipment in the water industry is:

- maintenance of water purity, both biological and chemical;
- approval for use;
- durability and low maintenance;

- ease of use;
- cost effectiveness;
- proven performance.

Maintaining water purity and approval for use

The most important factor in making water fit to drink is removal of bacteria and parasites. The water must then be kept clean and safe during storage and distribution, which requires both resistance to residual disinfectants and systems of high integrity. The corrosion resistance of stainless steels make them suitable to meet these requirements in both treatment facilities and distribution networks.

There have been many tests undertaken on the leaching of metal ions from stainless steel into drinking water.[1] All have shown levels well below those allowed by the European Drinking Water Directive 98/83/EC. The UK Drinking Water Inspectorate summarised its tests thus: "… the use of products made from the specified stainless steel grades [1.4307, 1.4404, 1.4462 and similar] in contact with water for public supply would be unobjectionable on health grounds."[2] There have been similar approvals for the use of stainless steels in other EU countries, in the USA and elsewhere. A European Approval Scheme for Construction Products in Contact with Drinking Water is being developed. Eurofer is actively engaged with its development and that of the associated test protocols.

The EU based its maximum permitted levels for metals on the World Health Organisation's Guidelines which at the time were 20 µg/L for nickel. Since then the WHO's guideline value for nickel has been revised upwards to 70 µg/L but there has not yet been any corresponding revision of the EU Drinking Water Directive maximum.

Durability and low maintenance

The low leaching levels of metal ions into drinking water are a direct consequence of the corrosion resistance of these stainless steels. From the designer's point of view, this corrosion resistance has other benefits:

- no need for a corrosion allowance;
- no need for a protective coating;
- no need to control water chemistry (except for adding a biocide);
- no need for a corrosion protection system;
- high flow rates are acceptable;
- disinfectants do not harm the equipment;
- equipment does not suffer degradation by corrosion;
- at the end of life, equipment is recyclable.

Nearly all of those factors contribute to the durability of the equipment and to comparatively low maintenance needs. Those are considerable benefits when seen against the annual cost of corrosion, which has been estimated as $36 billion for the water and sewage systems in the USA.[3]

Full recyclability of materials at end of life is an important consideration for an industry which is as conscious of its environmental impact as the water industry.

Other characteristics of stainless steels

The strength of stainless steels means that thin walled pipe designs are possible, even where yield strength is the limiting factor. The duplex grades have a particular advantage in this respect, offering twice the yield strength of the traditional 300 series stainless steels. At the same time, the ductility of stainless steels allows tees to be pulled directly in pipe walls, thus simplifying assembly. Similarly, the ends of pipes can be flared to allow either bell and spigot joints to be made or loose backing flanges to be used. Advantage can be taken of the ready weldability of stainless steels to design high integrity systems which not only reduce water loss but also prevent ingress of pathogens and other contaminants.

Lightweight construction

The above characteristics can be combined so that stainless steel equipment may be lighter than similar equipment constructed in other materials. That has advantages in reducing the carrying capacity of transport and installation equipment as well as of support structures, see Figure 1.

Figure 1. Installation of 300 mm drinking water piping in a sports stadium in Detroit, USA.

More shop and less site fabrication may be possible. Overall, that makes for better control, lower installation cost and a smaller site footprint. More importantly from a sustainability point of view is the reduced material intensity – less material is needed to achieve the same output.

Cost benefits

The cost of using stainless steel is always under scrutiny, particularly at times of high alloying element costs. However, the above discussion shows that it is necessary to take more factors into consideration than just the prevailing price per tonne of material. For example, a study of the installed cost of distribution piping in the USA showed that whilst ductile iron was lower cost in smaller sizes, above 300 mm (12 inches)diameter, the cost advantage favoured stainless steel because of the thinner wall, lighter weight and consequent ease of installation, see Table 1.

Table 1. 2003 costs of stainless steel distribution piping relative to ductile iron.

Nominal Pipe Diameter Inches	Relative Total Cost Comparison Per Linear Foot* 2000LF Project using 40 foot lengths of S.S. Pipe Pipe Material and Diameter				
	Ductile Iron Class 51	304 Sch. 10	316 Sch. 10	2304 Sch. 10	2205 Sch. 10
6	1	1.03	1.11	1.22	1.45
8	1	1.06	1.15	1.27	1.57
10	1	1.09	1.20	1.34	1.63
12	1	0.82	0.91	1.02	1.26
14	1	0.69	0.75	0.96	0.99
16	1	0.69	0.76	0.97	0.98

There may not always be an initial cost benefit for stainless steel. Then it is necessary to look at the resulting operating and maintenance costs by carrying out a life cycle cost study. The necessary discounting calculations are straightforward if the costs are available but it is very important to understand which factors will be the real drivers behind material choice for a particular project. For example, in some projects, reduced leakage and increased plant availability have been the key factors.

From knowledge to application

The body of knowledge about the characteristics and behaviour of stainless steels in water industry applications has been built up over many years. Information can be found in many technical publications and articles. The International Stainless Steel Forum has provided access to many of these through its website www.worldstainless.org. Engineers need straightforward practical guidance on grade selection, design and fabrication because in most cases these will not be prescribed by the codes and standards. Guidance has been produced by the national stainless steel development associations (SSDAs), often in conjunction with a local water industry body – for example, in the UK[4], Germany, Italy and France. Crucially, these guidance documents give confidence in the use of stainless steel by showing how to obtain best performance in practice and how to avoid pitfalls: for example, minimising the risks of crevice corrosion and microbiologically influenced corrosion. These documents are also closely related to the local national standards and approvals because without those it is very difficult to introduce and make use of a new material. Although it has been used in many countries for well over a quarter of a century, stainless steel is still regarded by many water engineers as a new material.

As an example of the need for practical guidance, the question often arises of whether or not heat tint after welding can be left on equipment when it goes into service. The best advice from the point of view of corrosion is to avoid it in the first place or to remove it. However, neither of those is completely practical in some situations. Studies have been made which indicate what degree of heat tint is likely to be acceptable in what circumstances.[5]

Individual companies will always promote their own products but the SSDAs have all been active in promoting the use of stainless steels in the water industry. They produce their own literature and put on seminars in their local language. The important concept is that of global messages being tailored for local delivery. In some cases, there is sufficient interest for national suppliers to work together in order to develop the market. This has happened for distribution piping in the USA (e.g. SPLASH, www.S-P-L-A-S-H.org), pipework in Japan (Japanese Pipe Club) and plumbing in Australia via the SSDA.

Technology transfer is important in getting more widespread use of stainless steel in water applications. That applies not only to the basic applications but also, more importantly, to innovative applications. For example, in many countries – especially in the cities - the distribution networks are now old and in need of replacement; the trenchless method developed to reline old mains in Italy with minimum traffic disruption, see Figure 2, has received wider interest.

Figure 2. Trenchless relining of a water main in a busy street in Padua, Italy

Figure 3 shows some of the different coupling methods available for stainless steel plumbing installations.

Figure 3. Stainless steel capillary, compression and press-fit plumbing fittings.

In conclusion, there are plenty of opportunities for greater use of stainless steels to meet the needs of the water industry around the world if the knowledge can be transferred to the market place.

Acknowledgement

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