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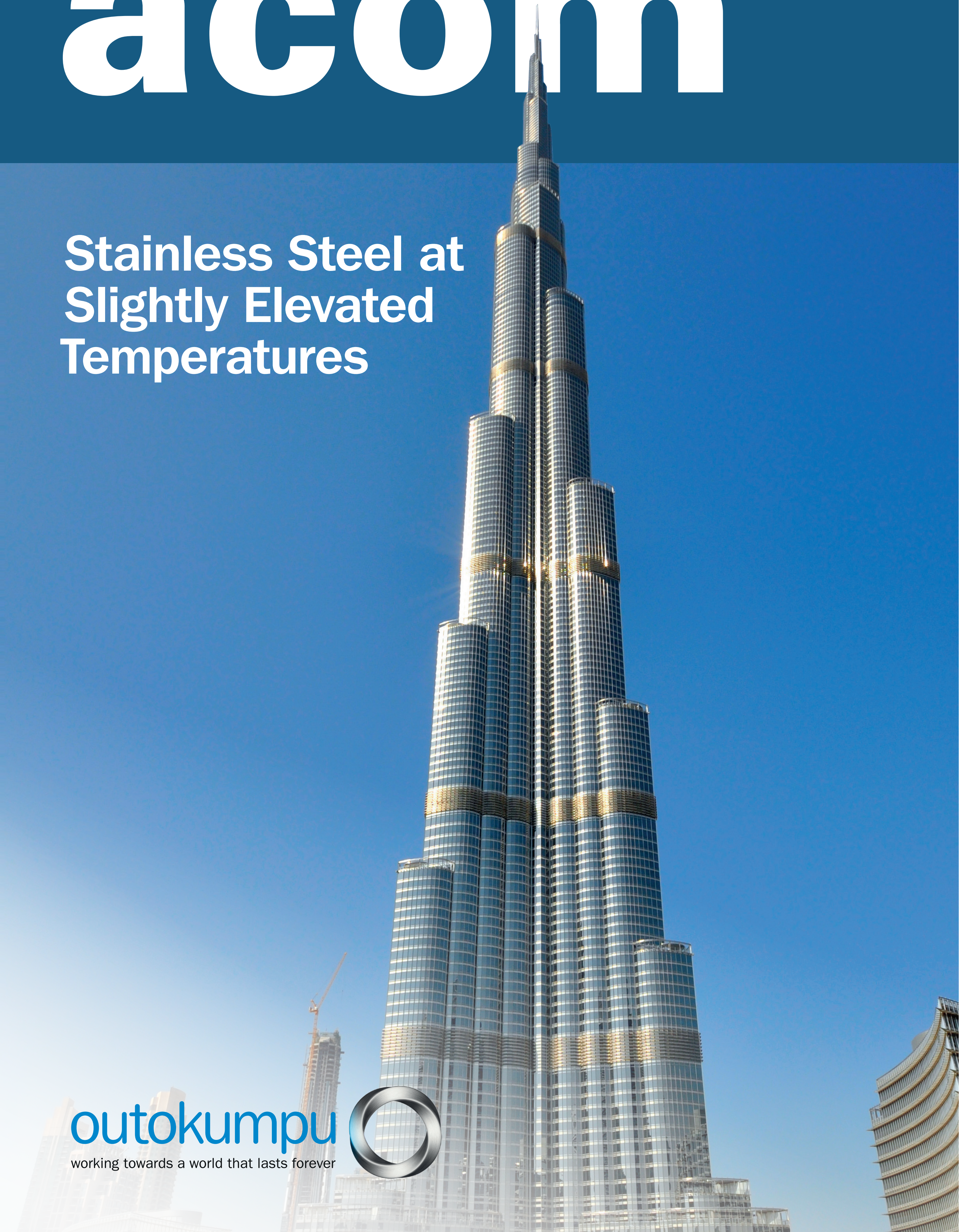

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Stainless Steel at Slightly Elevated Temperatures

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Abstract

The mechanical properties at slightly elevated temperatures will be discussed. It is so that the drop in strength is quite drastic when the temperature increases over room temperature (RT) or 20 °C. This is a drawback of current design practice and leads to a too conservative design. Today different testing parameters and standards are used for the room temperature and the elevated temperature tensile tests. Some recent tests will be presented and compared with traditional standardized data for a standard austenitic grade and a high strength duplex stainless steel. It is shown that much of the drop in strength is highly related to the testing parameters being applied. Finally a proposal will be discussed how to handle the slightly elevated temperatures in the design for a more efficient structural design.

Key words: mechanical properties, elevated temperatures, design codes, Eurocode, tensile testing

1 Introduction

Many buildings, bridges, storage tanks and other infrastructure and industrial outdoor applications are designed for a maximum temperature of 40 to 60 °C in the warmer parts of the world. One example of a location where this is the case is in Qatar Foundation new headquarters in Qatar, shown in Figure 1. A part of the beam structure, made in grade Forta DX 2205, for the building is shown in Figure 2.

The drastic drop in strength between RT and 40 to 60 °C has been noted by designers and also by the standardization authorities in the building and construction sector. The drastic drop in strength makes the stainless steels less attractive compared to carbon steels, as thicknesses and total weight will be increased to compensate for the lower strength values. This is an issue for stainless steels and not for carbon steels as the carbon steels has no or a very minor drop in strength at the slightly elevated temperatures.

This question has been raised by the Steel Construction Institute in the UK and they have made a proposal how to handle stainless steel constructions for the "slightly elevated temperatures" since these temperatures are quite common in the building and construction sector [1, 2].

One can divide the strength into four different regions using the mechanical strength values in European standards for austenitic and duplex stainless steels as function of the temperature (from room temperature and up). Firstly, from room temperature (RT, about 20 °C) up to 100-200 °C, where there is a significant drop in strength. Secondly, between 200-550 °C the strength is relatively constant with only a minor drop. The third region is above 550 °C, where the creep properties of the material play a more and more important role with increasing temperature. Even though we are considering the proof strength, $R_{p0.2}$, or tensile strength, Rm, the time dependency of the material will drastically decrease the strength as the temperature increases. In the fourth region, below RT the strength increases slightly and in an almost linear way as the temperature decreases. For most outdoor applications, however, the strength at RT is used as design strength for the lower temperatures. The definition of HT (high temperature) in the testing standard is a temperature of about 40 °C and above. In the present paper, only the slight elevated temperatures "In the sun" will be covered, i.e. only a part of the first region (RT to 100 °C) with the significant drop in strength above RT.

Figure 2 Detail of beam structure for the Qatar Foundation New Headquarters. Beams in grade Forta DX 2205. In total 170 tons of structural sections; 179 hollow sections in 17 different dimensions and 35 different L-profiles. Picture courtesy of Astad project management.

Figure 1 Qatar Foundation New Headquarters. Picture courtesy of Astad project management.

2 Room and elevated temperature tensile testing parameters

There are several testing standards for determination of the mechanical properties. With mechanical properties we mean $R_{p0.2}$ (0.2 % proof strength), $R_{p1.0}$ (1.0 % proof strength), Rm (tensile strength or Ultimate Tensile Strength, UTS) and A (elongation at fracture). The first three being of importance and therefore covered in the present paper.

The testing parameters in terms of stress and strain rates used in different standards are given in Tables 1 and 2 below. These are values applicable to stainless steels. There are some things that are worth noting in these tables. First, there are different tensile testing standards for RT and HT. The present standards used in Europe, EN ISO 6892-1 and EN ISO 6892-2 for RT and HT testing respectively give the user a lot of options, first in terms of an overall “method” and then several options (R1, R2, …) for different testing parameters for both determining proof strength and tensile strength at both RT and HT. This gives a possibility for a large variety in the testing procedures. The testing parameters commonly used for stainless steels are the ones given in the Tables 1 and 2. A perhaps interesting observation is that the RT strength and HT strength have sometimes been handled by two different departments traditionally and historically at many research labs, not being optimal from a co-ordination point of view.

From a mill perspective, the time it takes to make a test is important so the selection of testing parameters is primary to fulfil the standards, both the EN-ISO and the ASTM-standard and to perform the test in a reasonably short time. If the HT testing parameters should be applied to the RT testing, the time needed for the testing will increase dramatically being roughly ten times longer.

RT Tensile testing	**Determination of Proof strength**		**After proof strength (2%)**
Allowable test speed according to	Strain rate [(mm/mm)/s]	Stress rate [MPa/s]	Strain rate [(mm/mm)/s]
(Old EN 10002-1) EN ISO 6892-1 (Meth A) ASTM A370	0.00025 – 0.0025 0.00020 – 0.00030 (R2) < 0.00104	6 – 60 N/A 1.15 – 11.5	< 0.008 0.0054 – 0.0080 (R4) 0.00083 – 0.0083
(Old EN) combined with ASTM	0.00025 – 0.001	6 – 11.5	0.0008 – 0.0080
EN-ISO combined with ASTM	0.00025 – 0.00030	N/A	0.0054 - 0.0080

Table 1 RT tensile testing and related standards.

HT Tensile testing	**Determination of Proof strength**		**After proof strength (2%)**
Allowable test speed according to	Strain rate [(mm/mm)/s]	Stress rate [MPa/s]	Strain rate [(mm/mm)/s]
(Old EN 10002-5) EN ISO 6892-2 Meth. A ASTM E21	0.0000167 – 0.000083 0.000056 – 0.000084 (R1) 0.000050 - 0.000117	N/A N/A N/A	0.0003 – 0.0033 0.00112 – 0.00168 (R3) 0.00067 - 0.0010
(Old EN) combined with ASTM	0.00005 - 0.000083	N/A	0.0003 – 0.001
EN-ISO combined with ASTM	0.000056 - 0.000084	N/A	No overlapping range

Table 2 HT tensile testing and related standards

3 Tensile tests at room temperature with different testing parameters

Tensile testing was performed on one standard austenitic grade EN 1.4307 and one austenitic-ferritic (duplex) stainless steel, EN 1.4162 (LDX 2101®), with chemical compositions shown in Table 3. Grade EN 1.4307 is a well established and low strength grade and EN 1.4162 is a relatively newly developed high strength grade.

The tests were performed at RT but using strain rates according to both RT and HT standards, see Table 4. These are the test parameters used at Outokumpu in Avesta. In the following testing with RT-test parameters will be named F (Fast test) and testing with HT-test parameters will be named S (Slow test).

The result of testing in RT is shown in Tables 5 and 6 and is illustrated in Figures 3 and 4 that show the results from three specimens tested using test parameter “F” and two specimens tested using parameter “S”. Change of strain rate (testing speed) results in difference in $R_{p0.2}$ and $R_{p1.0}$ of roughly 25 MPa less for testing parameter “S” compared to “F” in the tests. According to our own experience this difference is within the range 20 – 40 MPa and Rm can be considered not to be influenced. The increase in Rm for grade 1.4307 is not typical. In Figures 3 and 4 R_{t2} (the strength at a total elongation of 2 %) is included as well. This strength was found to behave like $R_{p1.0}$ and was not investigated further.

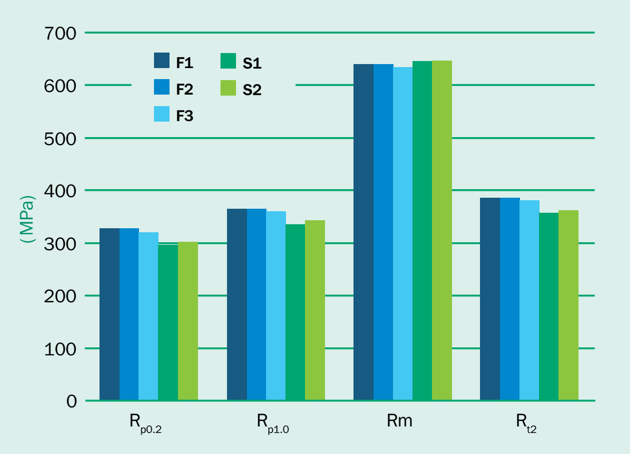

Figure 3 Influence of testing speed fast “F” and slow “S” for grade 1.4307 at RT.

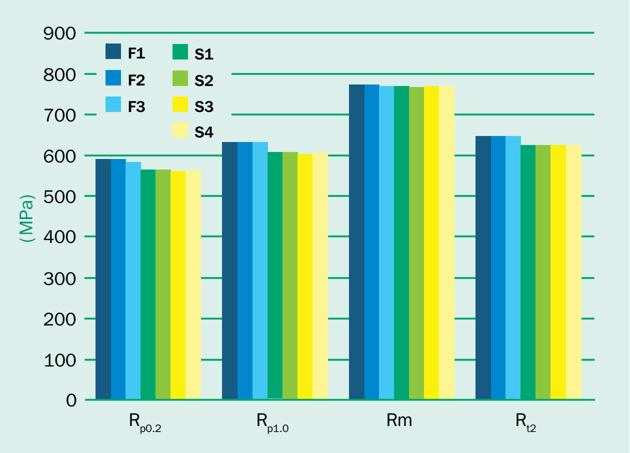

Figure 4 Influence of testing speed fast “F” and slow “S” for grade 1.4162 at RT.

Grade	C	N	Cr	Ni	Mo	Others
EN 1.4307	0.02	–	18.1	8.1	–	–
EN 1.4162/LDX 2101®*	0.03	0.22	21.5	1.5	0.3	5 Mn, Cu

Table 3 Typical chemical composition of the grades tested in % weight.

* LDX 2101 is a trademark owned by Outokumpu Oyj.

Test case	Test conditions
RT: Test parameter F	Tested at strain rate 0.001/s up to 2% and then changed to 0.008/s
HT: Test parameter S	Tested at strain rate 0.000083/s up to 2% and then changed to 0.001/s

Table 4 Test parameters used in the tensile testing.

	$R_{p0.2}$ (MPa)	$R_{p1.0}$ (MPa)	Rm (MPa)
Test parameter F	326	364	637
Test parameter S	299	340	646
Strength difference	-27	-24	+9

Table 5 Influence of testing speed for grade 1.4307 at RT. Mean values.

	$R_{p0.2}$ (MPa)	$R_{p1.0}$ (MPa)	Rm (MPa)
Test parameter F	588	632	773
Test parameter S	564	606	770
Strength difference	-24	-26	-3

Table 6 Influence of testing speed for grade 1.4162 at RT. Mean values.

4 Tensile tests at RT/HT and the strength in standards

This section will compare and discuss strength measured in the tests made with the difference standardized values. One can see that there is a quite drastic drop in strength between RT and 100 °C when looking at the mechanical strength values as a function of temperature in the European standards for austenitic and duplex stainless steels as shown in Figures 5 and 6 for the two grades investigated in the Cold Rolled (CR) condition. The trend lines in these figures are just derived mathematically and they are not representing any measured values. What we can see is that the standard strength values drop much more than what can be expected. Further on, there is no hardening phenomena or other metallurgical effect that can explain this large drop.

In Figure 7 all data from standards and testing are shown for Cold rolled (CR), Hot Rolled Coil (HRC) and Plate (P) over the temperature interval from RT up to 100 °C. The test results are the curves with “F” or “S” respectively.

Another way of representing the strength is by using so called retention curves. That means the strength values at the elevated temperatures are divided by the strength at RT which gives relative strength values between zero and one that can be used in the comparisons and in calculations.

The retention factors for standardized 0.2 % proof strength for all product forms derived from standard EN 10088-2:2014 are shown in Figure 8. What is worth noting is the great drop in strength which is between 0.67 and 0.85 at 100 °C. The CR condition has the greatest drop in strength and condition P has the lowest. In Figure 9 the CR-values from the standard are shown together with the values from testing. The results from testing show that the retention between 0.8 and 0.85 at 100 °C is being quite different from the one obtained from the standardized strength values.

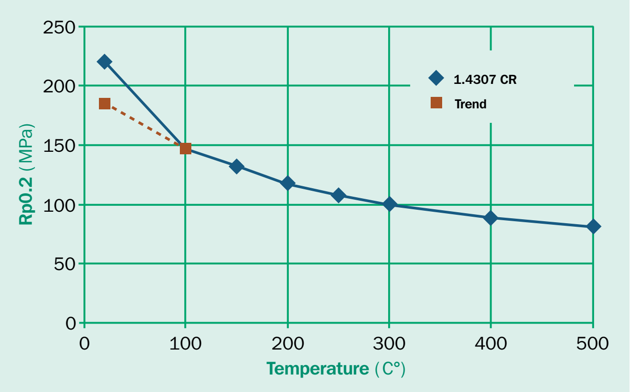

Figure 5 Proof strength as function of temperature for grade 1.4307 in Cold Rolled condition according to EN 10088-2:2014.

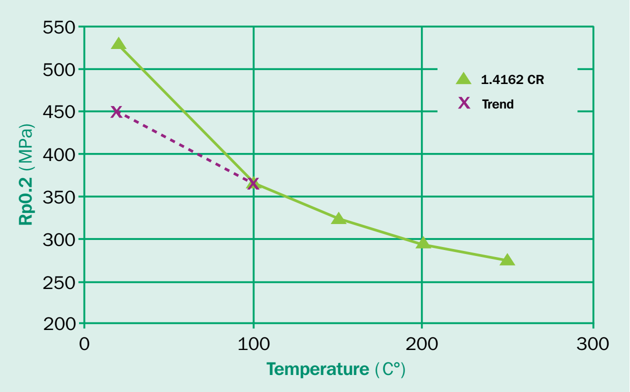

Figure 6 Proof strength as function of temperature for grade 1.4162 in Cold Rolled condition according to EN 10088-2:2014.

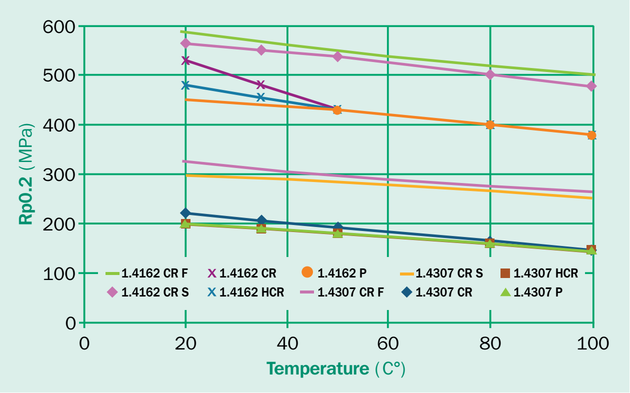

Figure 7 $R_{p0.2}$, for the investigated steel grades from standard EN 10088-2: 2014 and from testing.

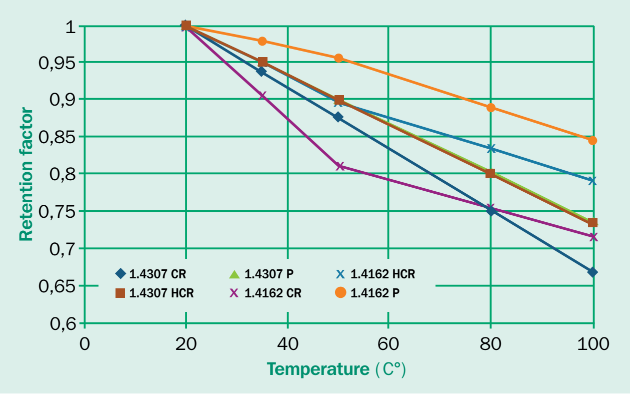

Figure 8 Retention factors for standardized 0.2% proof strength in EN 10088-2:2014.

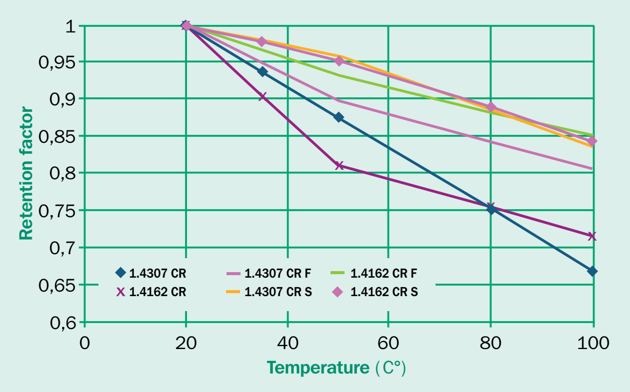

Figure 9 Retention factors for tests and standardized 0.2% proof strength for CR in EN 10088-2:2014.

5 Discussion and proposal on how to use slightly elevated strength data

Looking at the mechanical strength values in European standards for austenitic and duplex stainless steels it seems that there will be a “room for improvement” in terms of structural efficiency if more realistic retention factors, or strength values can be applied for applications subjected to temperatures slightly above RT.

One way of illustrating the possible increase in material strength utilization is shown in Figure 10, where the tested strength is divided by the standardized strength. The trend that the strength can be used more efficiently at the slightly elevated temperatures can be seen.

One proposal for a more realistic retention factor was presented in [1] giving a retention curve that is 1.0 up to 50 °C and then equal to 0.9 over 50 °C up to 80 °C. The advantage of this curve is that it is easy to handle and that constant strength values can be used in most cases (i.e. up to 50 °C). The proposals 1 and 2, shown in Figure 11, are the ones that have originated from this study. Proposal 1, which is a linearization of the SCI-proposal based on the testing data, is valid up to 80 °C. Proposal 2 is valid up to 100 °C and gives slightly lower values than Proposal 1. However, as for giving a limit of “slightly elevated strength” that might be defined as temperatures below 100 °C. It is suggested that the Proposal 2 is only valid up to 80 °C. This is based on the fact the strength is tested with the same testing parameters at RT and at the elevated temperatures.

If this concept is introduced it might also influence other disciplines as well. One design case that is directly influenced is the retention curves for fire design. Figure 12 shows the retention factor for grade 1.4162 together with a modification that has been made with the findings being made in present paper. Here it is also evident that some slightly higher values may be applicable, especially in the temperature range up to about 600 °C.

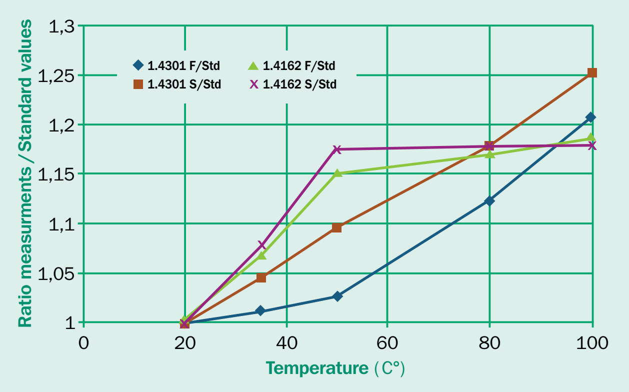

Figure 10 Increase in material strength utilization.

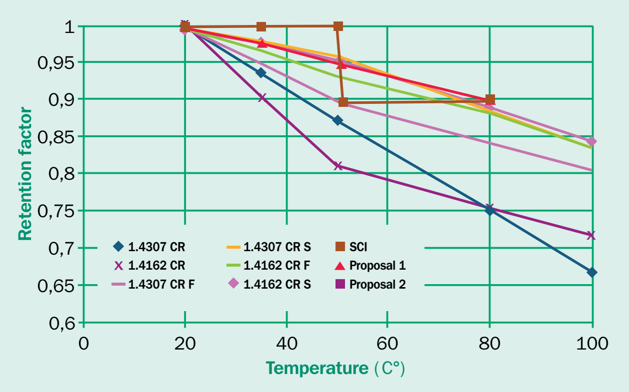

Figure 11 Retention factors for standardized 0.2% proof strength in EN 10088-2:2014 together with three different proposals, 1 and 2, and from SCI [1, 2].

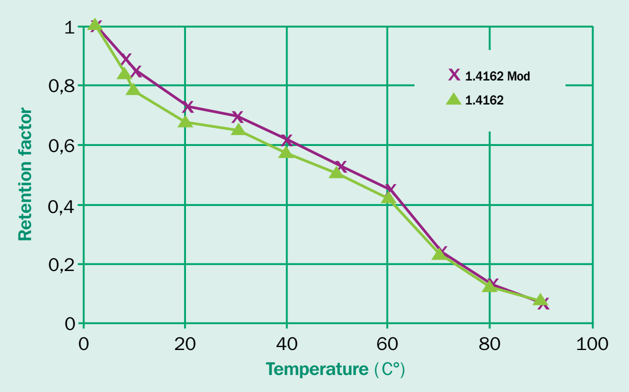

Figure 12 Fire design retention curve for grade 1.4162 from standard and a modified curve that has been corrected with tests being made at same testing conditions at RT and HT.

6 Conclusions

It is shown that much of the drop in strength is highly and solely related to the testing parameters and that “high temperature” in the traditional way of testing and testing procedures starts already just above 20 °C. The present investigation showed the reason for the drop in strength and finally proposed how to handle the slightly elevated temperatures “In the sun” in the design process and also how a fire design curve (strength retention curve) can be modified for a more efficient design. The main conclusions are:

1. The drop in strength from RT to +35/50/80/100 °C is a consequence of the test procedures in the testing standards.
2. Test at “slightly elevated temperatures” with own procedure using same testing parameters at all relevant temperatures. Let this be separated from traditional HT-testing used for design at higher temperatures.
3. Make proper retention design curve to new and old data based on steel type/grade. Three possibilities at least. To be further discussed which to be used.
4. Retention value increase roughly 0.15 at 80 °C and between 0.08 – 0.15 at 50 °C, according to Proposal 1 and 2. This is a significant improvement which potential should be utilized in structural design.

6. References

[1] AISC Design Guide 27: Structural Stainless Steel, American Institute of Steel Construction, 2013

[2] Baddoo, N., SCI, UK, Private communication.

Paper presented at the 13th Nordic Steel Construction Conference (NSCC),
23-25 September 2015, Tampere, Finland.

1582 EN-GB, Art 58, 12, 15.

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