Use of Duplex Stainless Steels at Low Temperatures

A New Way to Present Toughness – Temperature - Thickness Data

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Abstract

This paper contains a proposal on how to treat the use of duplex stainless steels at low temperatures, less than 0 °C. It is a common view that the duplex stainless steels may be used down to -40 °C, regardless of thickness, and for temperatures lower than -40 °C possible brittleness problems might occur and extra testing, inspection and a lot of extra work is needed in order to enable the use of the duplex grades. The approach presented gives a little more balanced picture of what temperatures the individual duplex grades can be used at, depending on the thickness. The approach is based on the European pressure vessel code, EN 13445 (2014), and specifically the part -2 “Materials”, that deals with, among other things, allowable materials for use at low temperatures, but presented in more “user friendly” way.

Keywords

Duplex Stainless Steel, Low Temperatures, Toughness, Fracture Toughness, Eurocode

1 Introduction

In the material standard EN 10028-7 (Materials for pressure vessels), the maximum thickness and the lowest temperature at which the grade can be used are given. The Maximum thicknesses for duplex grades is normally between 50 to 75 mm and the demand for the impact toughness at -40 °C, in the transversal direction, to be minimum 40 J and this is very often stated to be the lower temperature for structural use of duplex stainless steels, irrespectively of the sheet/plate thickness. The impact toughness demands on duplex stainless steels for flat products in Europe are found in:

- EN 10088-2 – “Stainless steels – Part 2: Technical delivery conditions for sheet / plate and strip of corrosion resisting steels for general purposes”. Maximum standardised thickness for duplex grades is typically 75 mm. This standard covers impact toughness criteria at room temperature only.
- EN 10088-4 – “Stainless steels – Part 4: Technical delivery conditions for sheet/plate and strip of corrosion resisting steels for construction purposes.” Maximum standardised thickness for duplex grades is also 75 mm. This standard covers impact toughness criteria at room temperature only.
- EN 10028-7 – “Flat products made of steels for pressure purposes - Part 7: Stainless steels” Maximum allowed thickness for 2205/1.4462 is 75 mm. For grades like 2304/1.4362, 2507/1.4410, 1.4507, 1.4501 it is typically 50 mm. General demand for the impact toughness at -40 °C in the transversal direction is minimum 40 J.

2 The Approach in European Pressure Vessel Code

In the current European pressure vessel code, EN 13445-2, Annex B [1], there are three different methods of handling materials at low temperatures. For tubes & pipes, EN 13480-2 – “*Metallic Industrial Piping - Part 2: Materials*”, handling materials at low temperatures is used in the same way and contains the same methods.

Section B.2.2 - Referred to as Method 1, is simply a list of materials and at what minimum temperature they may be used. It contains mainly carbon steels and austenitic stainless steels generally and austenitic stainless steel nuts and bolts for cryogenic applications.

Section B.2.3 Method 2, “Material selection and impact energy requirements”, gives an approach for how to handle carbon steels and duplex stainless steels at low temperatures.

Section B.2.4 Method 3, “Fracture mechanics analysis”, gives the user an option to verify his design using fracture mechanics and FE-analysis. This is a method that can be used if the pressure vessel is outside of the current limits. Method 3 can be very expensive if new fracture mechanics data needs to be generated.

The methods 1 or 2 shall be used to determine the impact energy required to avoid brittle fracture. Alternatively, Method 3 may be used to determine the required toughness. The method used shall be fully documented, in order to ensure that compliance can be verified.

In the following, Method 2 is used for the proposal being made.

The requirements given in Method 2 are as follows: (Text mainly from the code)

Method 2 applies to austenitic-ferritic (duplex) steels with a specified minimum yield strength ($R_{p0.2}$) ≤ 550 MPa. The strength in the rolling direction is the one that is lowest and that has to be considered.

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This Method 2, based on fracture mechanics [2] can be used to determine the requirements to avoid brittle fracture in these steels, and may be used at a design reference temperature, T_R, which is lower than the value derived by Method 1.

In this procedure the design reference temperature, T_R, is not equal to the impact test temperature, T_{KV}.

Distinction is made for as-welded (AW) and post weld heat treated (PWHT) condition. Only AW available for duplex.

The method is based on a set of three nomograms, see Figures 1 to 3. The diagrams show the relationship between T_R and T_{KV} depending on reference thickness, e_B, and strength level. Reference thickness e_B for constructional details is defined in Table B.4-1 in EN 13445-2 and it is normally the largest thickness appearing in the construction or in the joint.

Linear interpolation between strength and thickness levels given in the Figures 1 to 3 is allowed.

Very important: Parent material, welds **and** HAZ shall meet the impact energy *KV* at impact test temperature T_{KV}.

Alternatively the next higher strength class or wall thickness can be used. Lower test temperatures than T_{KV} are admissible for the same requirements.

If the pressure vessel is designed with low stresses in the shell a temperature adjustment may be made according to a table in Method 1. This is not considered in the present proposal, as we assume that the material is used with high design strength for static conditions.

Extrapolations for temperature ranges beyond the temperature ranges as given in the nomograms are not permissible. Outside the limits of this approach, Method 3 could be used.

For wall thicknesses < 10 mm the curve for 10 mm shall be used.

The impact energy requirements for different strength groups of austenitic-ferritic stainless steels are given in Table 1. Basically it is 40 J for standard 10 × 10 mm test specimens and the required energies for the sub-sized specimens are given for 10 × 7,5 mm specimens: 30 J, and for 10 × 5 mm specimens: 20 J.

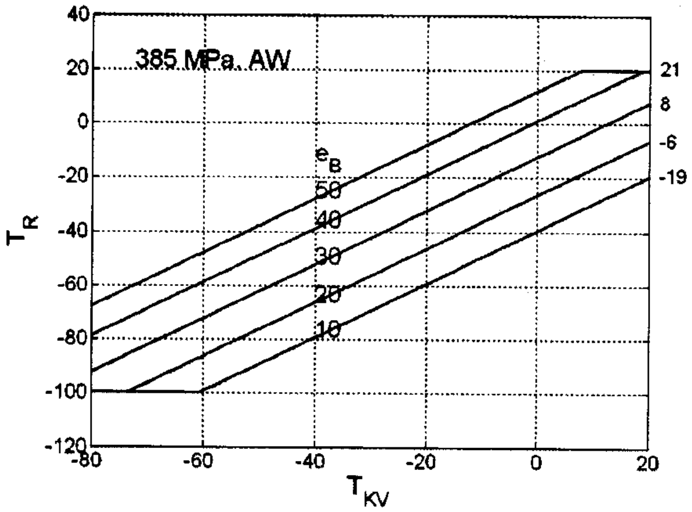

Fig. 1 Nomogram from Figure B2-9 in EN 13445-2:2014. Valid for 2304/1.4362.

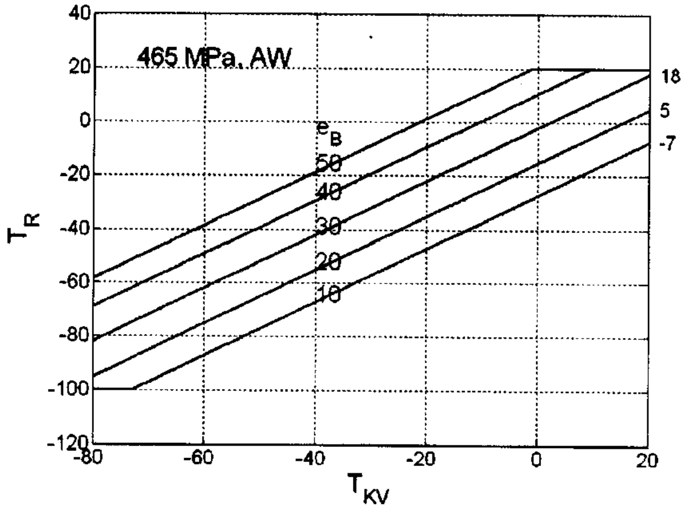

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Fig. 2 Nomogram from Figure B2-10 in EN 13445-2:2014. Valid for 2205/1.4462.

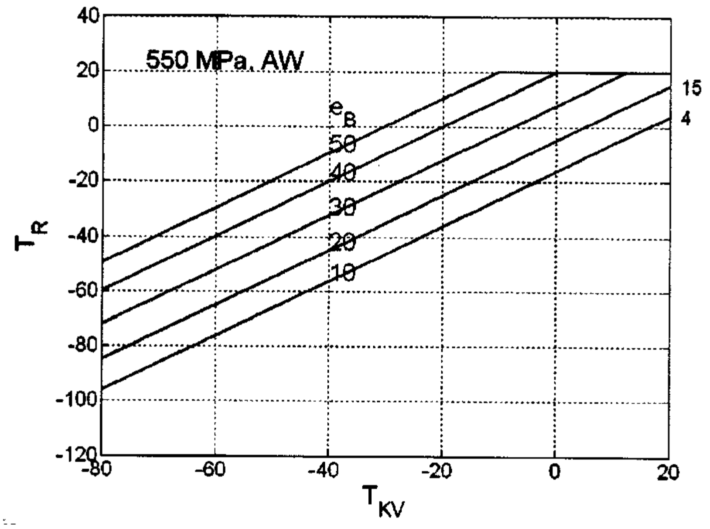

Fig. 3 Nomogram from Figure B2-11 in EN 13445-2:2014. Valid for 2507/1.4410, 1.4507 and 1.4501.

Table 1 Impact energy requirements for different strength groups of austenitic-ferritic stainless steels (For Methods 1 and 2) From EN 13445-2:2014, Annex B: Table B.2–14

Group (Min. strength in L-direction in MPa)	Required impact energy *KV* (on 10 × 10 mm test specimen)	Figure defining required T_{KV} for all applications
Re ≤ 385	40	1 B.2-9 in EN 13445-2
Re ≤ 465	40	2 B.2-10
Re ≤ 550	40	3 B.2-11

Table 2 Mechanical properties at room temperature and impact energy at -40 °C of duplex stainless steels in the solution annealed condition (min values) for plate. From EN 10028-7:2007 Table 10.

Grade	$R_{p0.2}$ (min) [MPa]	R_m (min) [MPa]	A_5 [%]	KV [J] (L(RT)/T(RT)/T(-40 °C))
2304/1.4362	385 (L)	630	25	120/90/40
2205/1.4462	445 (L)	640	25	150/100/40
1.4507	475 (L)	690	25	150/90/40
2507/1.4410	515 (L)	730	20	150/90/40
1.4501	515 (L)	730	25	150/90/40

Duplex stainless steels need to be tested to the above impact energy requirements in Table 2 to ensure that toughness is adequate. In contrast, austenitic stainless steels are *always* assumed to have adequate toughness and do not need to be tested.

The nomograms are used as follows and illustrated in Figure 4.

- Start selecting the nomogram valid for the strength level of the grade you want to evaluate. In this case 2205/1.4462.
- Then select an impact testing temperature, T_{KV}, e.g. -40 °C.
- Select the reference thickness, e_B. In this case 20 mm.

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- If this test gives an impact value > 40 J, then it is allowed to use the 20 mm sheet down to -58 °C. If the test temperature was -60 °C and the 40 J requirement fulfilled, then the plate have been allowed to be used down to about -75 °C

This might be seen as a little strange, but as it is stated in the background: In this procedure the design reference temperature, T_R, is not equal to the impact test temperature, T_{KV}.

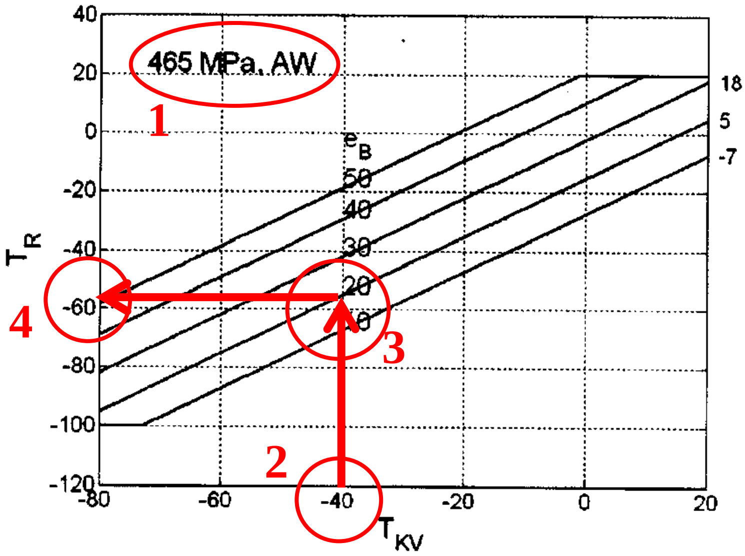

Fig. 4 How to use the nomograms. Example valid for 2205/1.4462.

By evaluating the nomograms at different impact testing temperature, T_{KV}, It is now possible to create a new diagram with temperature on the x-axis, thickness on the y-axis and impact toughness requirement, 40 J, at different temperatures, (T_{KV}, T_R, e_B) → (T_R, e_B, T_{KV}). The limits of T_R at -100 °C and +20 °C and thickness, e_B, give the limits of the axis in the new diagrams.

3 New Curves for Duplex at Low Temperatures, Accounting for Different Thicknesses

After this transformation is made, the three Figures, 5 to 7, have been obtained. This gives a much clearer picture of the information in the original nomograms in Figures 1 to 3.

The curves in Figures 5 to 7 should be interpreted as follows. The green boundary line covers the area of combinations of thicknesses and design temperatures where the grade in question can be used and when the grade satisfies the impact toughness demand of 40 J at -40 °C. This is what is normally guaranteed for duplex grades 2304/1.4362, 2205/1.4462 and 2507/1.4410, so being within this area is in accordance with this approach.

Then curves are evaluated in the same way for lower impact testing temperatures, T_{KV}, -50, -60 -70 and -80 °C. The red curve for impact testing temperature, T_{KV}, of -80 °C fulfilling 40 J, gives the outer/lower limit of this method. The curves in between show the limits for lower impact testing temperatures, T_{KV}, -50, -60, and -70 °C.

In the area outside the red boundary where it is "Not possible to use ..." it might still be possible to use the duplex grade, by using EN 13445, Section B.2.4 Method 3, "Fracture mechanics analysis", but that method requires its own verification, as mentioned before.

According to this approach it is permitted to use a 50 mm duplex at -40 °C. For this case, the impact toughness of 40 J has to be verified with tests at -60 °C.

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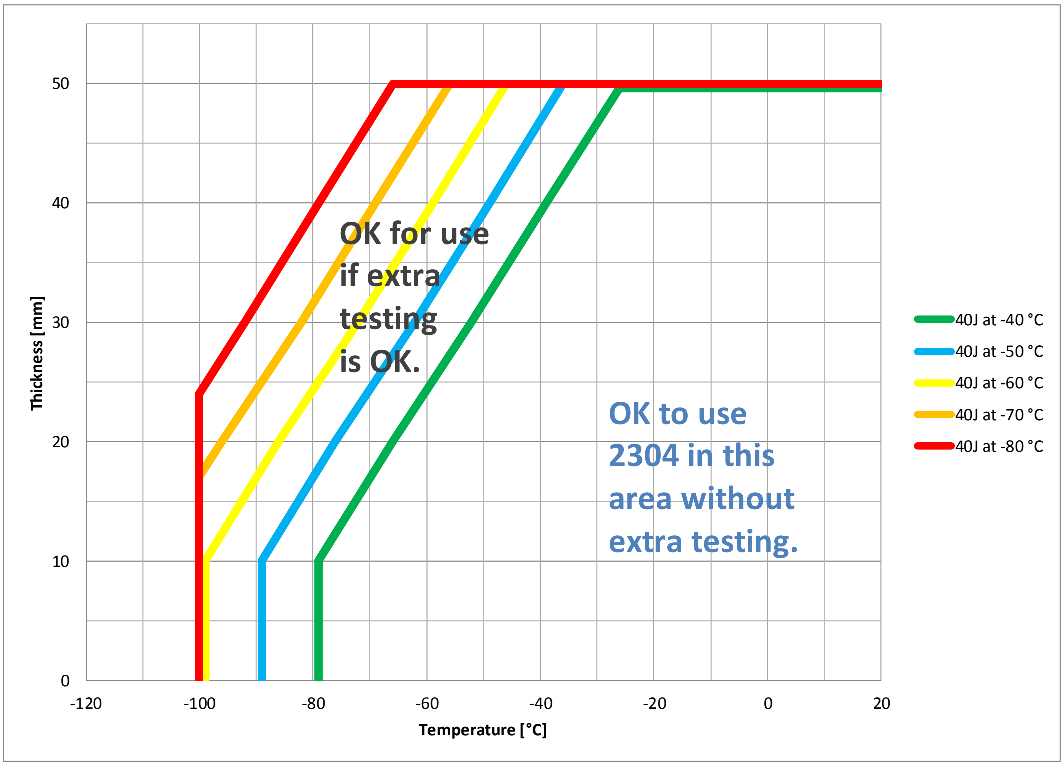

Fig. 5 Temperature - thickness map for grade 2304/1.4362 as derived from Fig. 1.

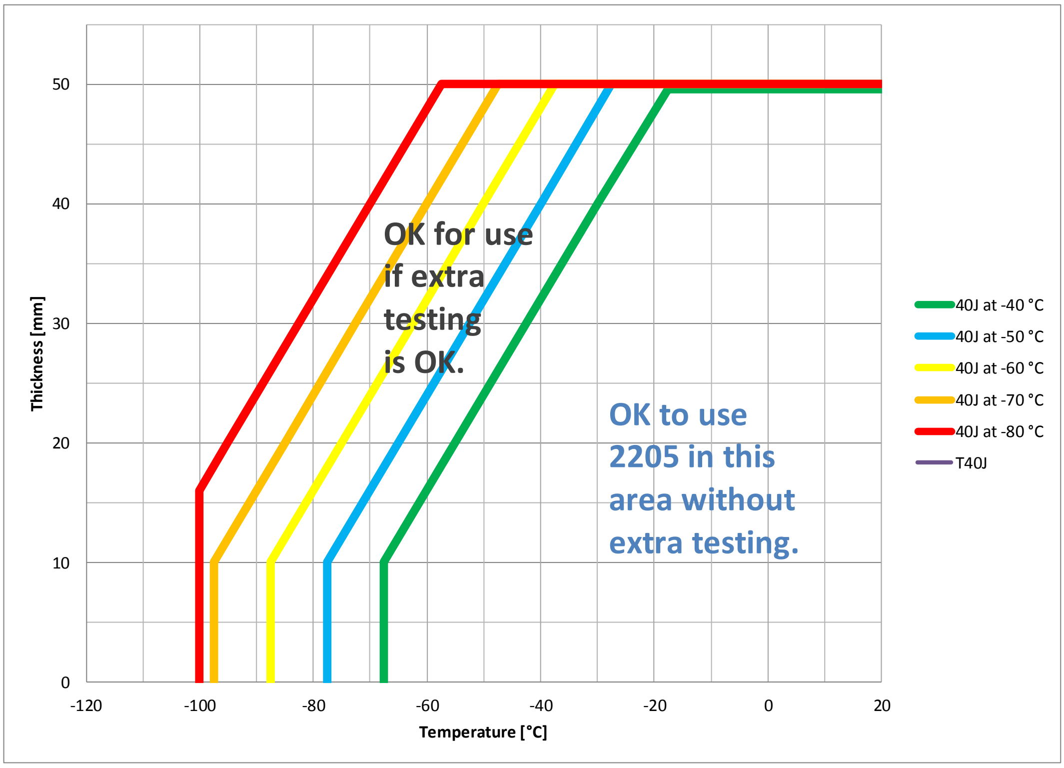

Fig. 6 Temperature - thickness map for grade 2205/1.4462 as derived from Fig. 2.

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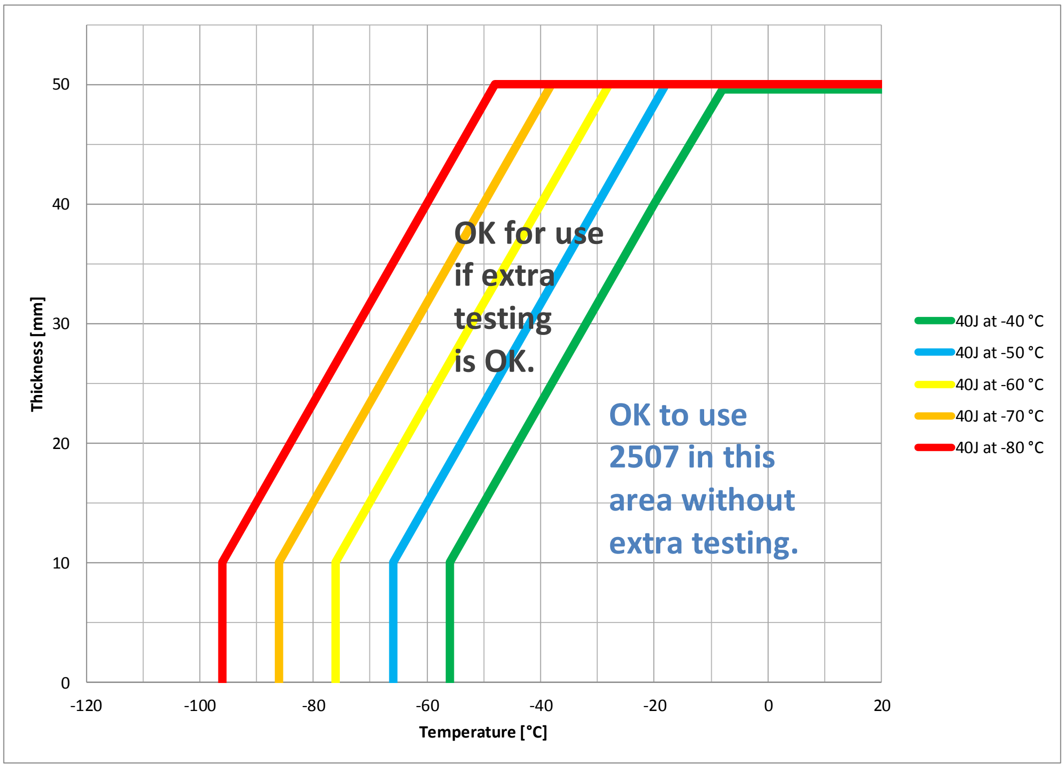

Fig. 7 Temperature - thickness map for grade 2507/1.4410 as derived from Fig. 3. Also valid for 1.4501 & 1.4507.

4 Influence of Welding

There are few investigations made on low temperature impact toughness on duplex stainless steels that can be readily used for the purpose of determining at how low temperature duplex materials can be used. Such temperature is denoted T_{40} or T_{40J} and is the minimum temperature that fulfils 40 J for a specific grade and thickness.

In the Ecopress project [3] such data was generated for the 2205/1.4462 grade. Figure 8 shows the T40 data from the ECOPRESS project together with unpublished data from Outokumpu. Three determinations of T_{40} for 10, 30 and 50 mm base material and four different welding conditions have been made. The T_{40} values have been determined from fitting the impact toughness data covering upper shelf temperature to the lower shelf temperature with the following equation (1):

$$C_V(T) = \frac{C_{V,US} - C_{V,min}}{2}\left(1 + tanh\left(\frac{T - T_{50}}{C}\right)\right) + C_{V,min} \quad (1)$$

were $C_{V,US}$ was the upper shelf energy and $C_{V,min}$ the lower shelf energy from experimental data and T_{50} and C the fitting parameters.

For the base material there is no problem to fulfil the requirement down to the lowest temperature on the limiting red curve as the T_{40} –value vas determined to ≤ -100 °C for all thicknesses.

Based on this study it seems evident that grade 2205/1.4462 may be used inside the limits of the red curve in Figure 6 and 8. This is a potential large expansion of the applications possible for the grade. The influence of welding method is evident and they give the limitations of the use.

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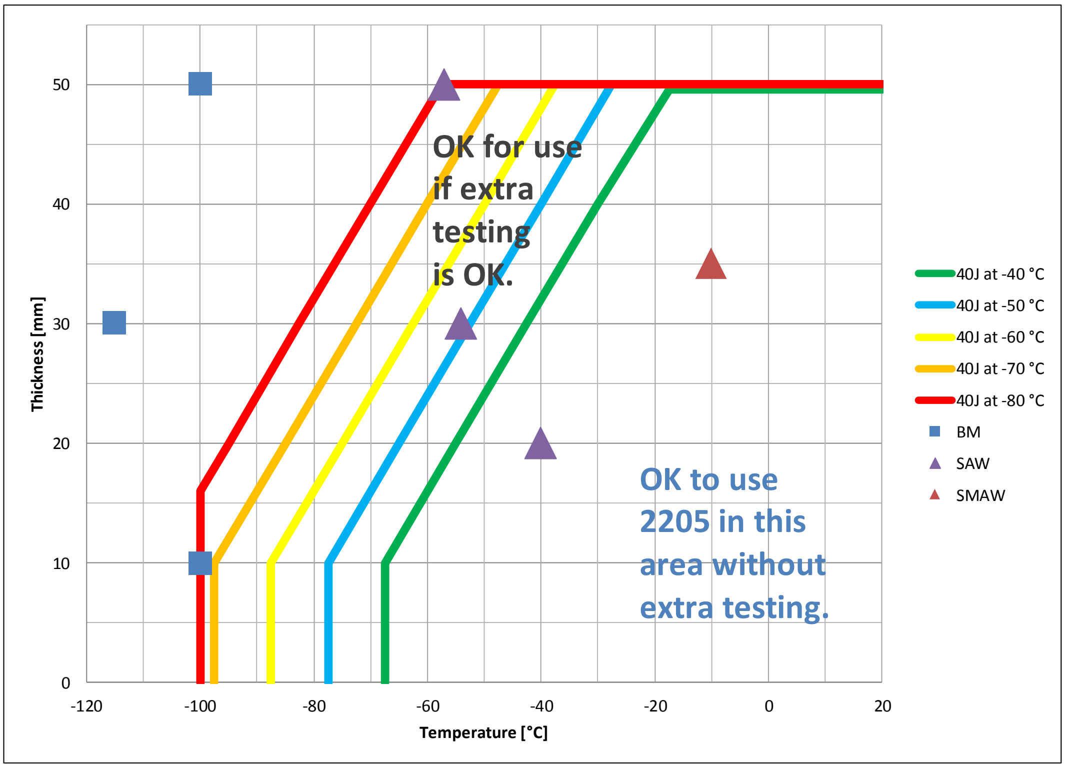

Fig. 8 **Temperature - thickness map for grade 2205/1.4462 with T_{40} for base material (squares) and weld metal for two different welding conditions (triangles).**

5 Conclusions

The way of presenting the thickness – temperature – toughness relation shown in the new type of figures shown in Figures 5 to 7 is a good way to illustrate the use of the duplex stainless steels at lower temperatures.

For base material of grade 2205/1.4462, the present approach shows large potential for expansion of applications into low(er) temperature applications.

This approach is derived from the European pressure vessel code, which is a strict design code in Europe. For other applications, like bridges, infrastructure installation and general use, demands may not be as strict as for pressure vessels, so for this type of applications, the present approach may be easy to adopt. The approach has the possibility to open up for new low temperature duplex applications.

References

[1] EN 13445-2:2014+C3:2016, Unfired pressure vessels – Part 2: Materials.

[2] R. Sandström and P. Langenberg, "Design Against Brittle Failure for Stainless Steel in the European Pressure Vessel Code EN 13445", Proc.-6th European Stainless Steel Conference, Helsinki, Finland, June 10-13, 2008, pp. 361 – 372.

[3] H. Sieurin, "Fracture Toughness Properties of Duplex Stainless Steels", PhD Thesis, KTH, 2006.

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