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A comparative study into the fracture toughness properties of duplex stainless steels

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ABSTRACT

Beside their high mechanical strength, duplex stainless steels are a suitable choice in highly corrosive environments. These types of steels are used in steel bridges more and more frequently exposed to low temperatures and fatigue loads. However, for low temperature applications, it must be guaranteed that brittle fracture is avoided since duplex stainless steel shows a toughness-temperature relationship similar to that of carbon steel. For this reason, in the frame of the German national FOSTA research project "P 1390", comprehensive investigations have been started into the material selection of duplex stainless steel to avoid brittle fracture considering the fracture mechanic based background of EN 1993-1-10. For this purpose, Charpy-V impact tests and fracture toughness tests have been systematically carried out for various duplex stainless steels in order to create the basis for the development of toughness requirements for new duplex classes. The validity of the already existing Master Curve concept and the applicability of the transition temperature correlation for duplex stainless steels based on experimental fracture toughness and Charpy-V impact tests have been investigated. The aim of this contribution is to present first results of these investigations.

1. Introduction

In the last twenty years, the use of duplex stainless steel has become more and more an interesting alternative for steel bridges instead of using carbon steel [1]. Duplex stainless steels offer an attractive combination of properties, including high mechanical strength, good corrosion resistance in highly corrosive environments, low maintenance costs and good weldability. Furthermore, duplex stainless steels obtain high toughness properties at low temperatures from the austenite crystallographic phase, while the ferrite content contributes to an improvement of the mechanical strength of the material.

Besides all these advantages, the prevention of brittle fracture is very important when steel bridges are exposed to low temperatures. The choice of material to avoid brittle fracture is covered in EN 1993-1-10 [2] for carbon steel material S235 to S690 while the currently published version of EN 1993-1-4 [3] refers to different types of stainless steel including duplex stainless steels (1.4062, 1.4162, 1.4482, 1.4662, 1.4362 and 1.4462) to be used only down to −40 °C service temperature. As it can be seen, EN 1993-1-4 covers some different types of duplex stainless steel, however the stated toughness requirements are insufficient for duplex stainless steels. For this reason, the rules have recently been updated in the revised version of the draft prEN 1993-1-4 [4] in such a way that maximum permissible element thicknesses depending on the stainless steel strength, its toughness quality, the applied stress level and the reference temperature are given in relation to the procedure used for EN 1993-1-10. Before the draft will be published, the given values of element thicknesses, which, in a first step, have been derived on the basis of Langenberg et al. [5], shall be checked with results from the presented investigations.

Different influencing parameters like weldments and its sub parameters like the welding process and type of filler material may have an influence on the fracture behaviour of the material [6]. Fracture toughness of both the base metal and weldments of duplex stainless steel were already investigated in different studies in the past [7–14]. The results show promising results at sub-zero temperatures. However, there are still some other parameters to be considered like the influence of the plate thickness on the fracture behaviour or the degree of cold forming on the transition temperature in order to develop a fracture mechanics based concept for duplex stainless steels to avoid brittle fracture. For this reason, in the frame of the German national FOSTA research project "P

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1390", a comprehensive investigation has been started to close these gaps.

2. Transition temperature correlation and master curve concept

One of the main objectives of this study is to verify the validity of the Master Curve concept and the applicability of the transition temperature correlation for duplex stainless steels as both were developed based on experimental test results for carbon steels. Based on EN 1993-1-10, the fracture mechanics concept relies on a transition temperature correlation combined with a Master Curve approach for temperature dependent fracture toughness [15,16].

Herein, the so-called modified Sanz-Correlation describes the transition temperature correlation between the temperature at a Charpy-V impact toughness of 27 J (T_{27J}) and the temperature at a fracture toughness of 100 MPa$\sqrt{m}$ (T100), see Eq. (1), [16–18]:

$$T_{100} = T_{27J} - 18 \pm 2 \bullet \sigma \tag{1}$$

where σ is the standard deviation (σ = 13 °C).

The Master Curve is given by Eq. (2) according to [19–21] to describe the fracture toughness of materials and weldments with $b_{eff} = 5\ a_d$ for plates with a semielliptical surface crack, a_d is the design crack depth at which brittle fracture occurs and P_f describes the failure probability:

$$K_{mat} = 20 + \left[77 \bullet exp\left(\frac{T - T_{100}}{52}\right) + 11\right] \bullet \left(\frac{25}{b_{eff}}\right)^{0.25} \bullet \left(ln\frac{1}{1 - P_f}\right)^{0.25} \tag{2}$$

It is important to acknowledge that the Master Curve method is primarily intended for materials displaying cleavage initiation. Cleavage within the ferrite phase, also present in the austenite-ferrite duplex microstructure, is mostly described by the known weakest link mechanism [22]. The austenite phase in the duplex stainless steel, however, tends to inhibit cleavage crack growth in the ferritic phase [23]. This mechanism does not lead to a fully cleaved fracture at the lowest temperatures, it does indicate fracture initiation and the corresponding fracture toughness level. Despite this known facts, different studies show that the Master Curve method as such is applicable as a practical tool [5,12,22,24,25]. The following described investigation is based on this and own studies because it was shown that the method can effectively describe the fracture toughness behaviour of duplex stainless steel, particularly in the ductile-to-brittle transition temperature region [22].

3. Experimental investigation

3.1. Material and preparation of the specimens

Duplex stainless steels benefit from the properties of both austenitic and ferritic stainless steels. They are formed by a two-phase microstructure with a phase balance of approximately 50% ferrite and 50% austenite. The austenite contributes to a high corrosion resistance and high toughness at low temperatures and the ferrite provides high strength and resistance to stress corrosion cracking [12,26].

The more highly alloyed duplex stainless steels, as exemplary 1.4462, display a very great corrosion resistance, especially to stress corrosion cracking. Beside chrome, nickel is one of the most important elements in the composition of such duplex stainless steels which is used as an austenite stabilizing element to increase the toughness [26,27–30]. However, high nickel prices have more recently led to a demand for replacing the costly nickel by more cost-effective manganese and nitrogen. Due to this cost factor, lean duplex stainless steels with lower nickel content started to receive a great deal of attention in recent decades in the industry [31]. For this reason, it is very important to verify a satisfactory fracture toughness for duplex stainless steels with low nickel content. Finally, in the presented study, 1.4462 and the lean duplex stainless steels 1.4162 and 1.4662 were included in order to investigate the influence of the nickel content on the impact and fracture toughness of these duplex stainless steels.

In the frame of the presented investigations, Charpy-V impact tests were performed for these three different types of duplex stainless steels with varying plate thicknesses: 1.4462 - thicknesses 25 mm and 80 mm, 1.4162 - thicknesses 25 mm and 50 mm as well as 1.4662 - thickness 25 mm. All different tested types of duplex stainless steels were commercially produced by Outokumpu. The chemical compositions of the investigated stainless steels are given in Table 1.

In this study, the influence of the weldment on the impact toughness behaviour of the material has been investigated as well. For this case, K-joint weldments were carried out using the Metal Active Gas (MAG) welding process using stainless steel plates 1.4462 (25 mm and 80 mm) and 1.4162 (25 mm and 50 mm). In order to have an increased toughness of the weldment, the welding consumable 22 9 3 N L was chosen which provides a higher nickel content for an improved austenite formation, see Table 1 and [6]. The selected welding gas was a combination of 98% argon (Ar) and 2% carbon dioxide (CO_2). The welding direction was parallel to the rolling direction. No post-weld treatment was applied on the welded plates. The welding parameters are presented in Table 2.

The influence of the degree of cold forming on the impact toughness of duplex 1.4462 and lean duplex 1.4162 with each a thickness of 25 mm was another parameter to be investigated. Cold forming was applied on 25 mm thick duplex strips in a 1600 kN servo hydraulic universal testing machine whereby the degree of cold forming was measured by means of a video extensometer. After unloading the duplex strips, the remaining amount of cold forming was recorded. Three different strips with different degrees of cold forming (4%, 9% and 11%) were prepared. Afterwards, Charpy-V impact test specimens were fabricated from these strips.

Furthermore, a total of 22 fracture toughness tests were carried out for 1.4462, 1.4162 and 1.4662 steels in different thicknesses.

3.2. Charpy-V impact tests

In total, 371 Charpy-V impact tests were performed for 1.4462, 1.4162 and 1.4662 duplex stainless steel base material, weldments and cold formed base material. Herein, the influence of the degree of cold forming was investigated for both 25 mm thick duplex 1.4462 and lean duplex 1.4162 stainless steel plates.

The Charpy-V impact tests were conducted according to ISO 148-1 [33] on a pendulum motion "Charpy 450 J" from Zwick/Roell at University of Duisburg-Essen, Institute for Metal and Lightweight Structures, Germany as shown in Fig. 1 (a) and (b). Charpy-V impacts tests offer a practical and worldwide accepted method to qualitatively assess the toughness behaviour of a material as a function of the temperature. The V-notch of the ISO 148-1 Charpy-V test specimens had a notch angle of 45°, a notch radius of 0.25 mm and a notch depth of 2 mm, see Fig. 1 (c). For the welded test specimens, the test specimens were fabricated with the notch placed in the heat affected zone (HAZ). For each test series, at least 21 tests were performed at different temperatures between room temperature down to about −196 °C. Fig. 2 shows some sample photos of fractured surfaces of duplex 1.4462 (25 mm) test specimens at different temperatures.

Based on the experimental results, hyperbolic tangent curve fittings have been conducted based on the Oldfield regression model [34] to achieve impact toughness transition curves, see Eq. (3). Herein, CVE is the Charpy V-notch energy in J, T is the temperature in degrees Celsius and A, B, and C are fitting constants. The applicable transition temperatures criteria, like T_{27J} or T_{40J}, have been determined by means of the achieved fitting curves.

$$CVE(T) = A \bullet \left[1 + tanh\left(\frac{T - B}{C}\right)\right] \tag{3}$$

The impact toughness transition curves for all different test series are presented in Fig. 3 in different groups in order to show the influence of

Table 1
Chemical composition (wt%) of base material and welding consumable.

	Element							
	Cr	Ni	Mo	Mn	Si	N	P	C
1.4462 (25 mm)	22.25	5.67	3.14	1.34	0.39	0.17	0.025	0.014
1.4462 (80 mm)	22.41	5.65	3.18	1.40	0.41	0.17	0.260	0.017
1.4162 (25 mm)	21.30	1.60	0.46	4.35	0.57	0.25	0.026	0.023
1.4162 (50 mm)	21.40	1.55	0.33	4.25	0.56	0.23	0.025	0.029
1.4662 (25 mm)	23.90	3.70	1.59	2.86	0.41	0.29	0.025	0.023
22 9 3 N L[1]	21.00–24.00	7.00–10.00	2.50–4.00	2.50	1.00	0.10–0.20	0.030	0.030

[1] Welding consumable according to ISO 14343 [32].

Table 2
Welding parameters.

Welding process	Root gap (mm)	Groove angle	Heat input (kJ/mm) ± 25%	Current (A)	Voltage (V)	Welding speed (mm/min) ± 10%
Metal Active Gas (MAG)	2	50°	0.8	160–190	24.9–27.6	350

the material, plate thickness, weldment and degree of cold forming on the transition curve behaviour. Table 3 presents the transition temperatures T_{27J} and T_{40J} for all test series.

As expected, it can be seen that the duplex stainless steel 1.4462 shows a higher impact toughness in comparison to the lean duplex stainless steels 1.4162 and 1.4662, see Fig. 3 (a). This phenomenon can be explained by the higher nickel content of 1.4462, see Table 1. The experimental results also indicate a higher transition temperature for 1.4662 with a higher nickel content than 1.4162, see Fig. 3 (a).

Additionally, as expected, the results show the obvious influence of the plate thickness on the impact toughness especially in the transition zone, see Fig. 3 (b). As it can be seen in Table 3, the T_{40J} values increase to higher temperatures with increasing plate thickness for both duplex 1.4462 and 1.4162 stainless steel plate materials.

The test specimens with a notch in the heat affected zone (HAZ) show noticeably lower impact toughness values and consequently higher transition temperatures in comparison to the base metal, see Fig. 3 (c) and (d) and Table 3.

As known from ferritic carbon steels, it can be shown for the duplex grades that cold forming has a similar influence on the impact toughness. As can be seen from Fig. 3 (e) and (f), with increasing degree of cold forming, the impact energy in the upper shelf region decreases and the transition temperatures increase.

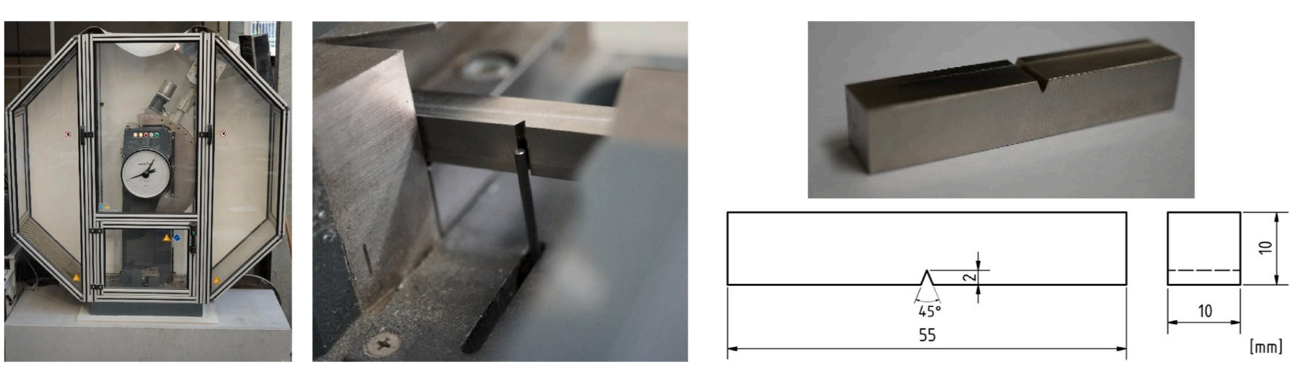
According to EN 1993-1-10, for non-ageing carbon steels, a 3 °C temperature shift of the transition temperature shall be considered for each percent degree of cold forming (see Eq. (4) with $\Delta T_{\varepsilon cf}$ is the adjustment for the degree of cold forming ε_{cf} in °C and ε_{cf} is the degree of cold forming in percent):

$$\Delta T_{\varepsilon cf} = -3 \times \varepsilon_{cf} \ [^{\circ}C] \tag{4}$$

The results obtained for both duplex 1.4462 and lean duplex 1.4162 show that each percent cold forming degree reduces the T_{40J} temperature by <3 °C ($\Delta T_{\varepsilon cf}/\varepsilon_{cf} < 3$) for all specimens with different degrees of cold forming, see Table 3. For this reason, the existing statement in EN 1993-1-10 seems to be somehow conservative for the investigated stainless steels. For this reason, up to now, it can be assumed that the temperature shift relationship of EN 1993-1-10 for covering the degree of cold forming is applicable to stainless steels as well.

3.3. Fracture toughness tests

The Charpy-V impact test is a qualitative test method since the results only allow the comparison of materials but cannot be used directly for the evaluation of components neither gives any information about how the material resists a crack from growing. In order to investigate the crack growth resistance of 1.4462 stainless steel, fracture toughness tests were performed and evaluated according to ASTM E1820-20b [35], using standard single-edge notched bend (SENB) specimens. The geometry of the test specimens was 25 × 50 × 230 mm, see Fig. 4 (a). Notches were machined in a way that the cracks grow in the rolling direction along the elongated microstructure of the material. The specimens were pre-fatigued at room temperature up to a pre-fatigued crack length of about 4 mm, providing an a_0/W value of 0.5. Side-grooves were machined with an angle of about 45° after the pre-fatigue has been introduced to ensure a straight crack front. The depth of the side-groove was 2.5 mm on each side, summing up to 10% of the original ligament width. The side-grooves help to have highest constraint (plain strain) across the specimen, also on the flanks where normally plane stress would dominate. The distance between the outer loading points of the SENB specimens was 200 mm. The fracture toughness tests were



(a) Testing machine (b) Position of the specimen (c) Geometry of the Charpy-V specimen

Fig. 1. Pendulum impact testing "Charpy 450 J" machine and geometry of the Charpy-V specimen.

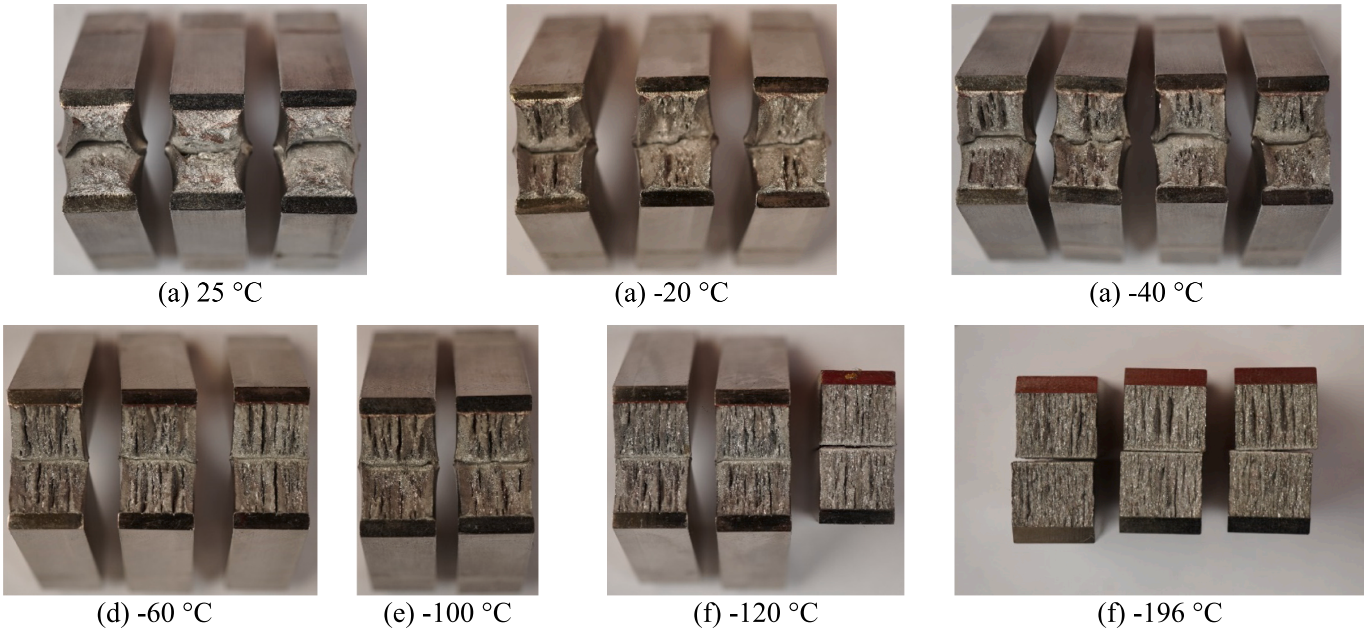


Fig. 2. Sample photos of fractured surfaces of Charpy-V test specimens of duplex 1.4462, 25 mm.

performed in a test rig containing a three-point loading fixture in a cooling box. Using liquid nitrogen, the cooling box can be cooled down to a testing environment temperature of minimum −150 °C, see Fig. 4 (b).

The construction line has been calculated based on Eq. (5) and Eq. (6) with σ_{YS} is the yield strength and σ_{TS} is the ultimate strength of the material in MPa.

The testing temperature could be held constant with ±0.2 °C during the entire testing. The SENB fracture toughness tests were carried out with a 100 kN hydraulic testing machine. The load was applied displacement controlled at a constant rate of 0.01 mm/s, while the crack mouth opening displacement (CMOD) was measured with a clip-gauge. The compliance method was used to carry out the fracture toughness tests. The SENB specimens were subjected to different loading/unloading cycles whereby the unloading ratio was set to 50% of the actual maximum load, see Fig. 5 (a). Up to now, fracture toughness tests were performed for 1.4462 stainless steel material of plate thicknesses 25 mm and 80 mm at different temperatures. Fig. 5 (b) shows exemplary the load-CMOD diagram for duplex 1.4462 (25 mm) at −150 °C.

Fig. 5 (c) and (d) exemplary show the J-Δa curves for 1.4462, 25 mm at −150 °C and 1.4462, 80 mm at −80 °C. Herein, J is the fracture energy per unit fracture surface area and Δa is the crack extension in mm.

$$J = 2\sigma_Y \Delta a \tag{5}$$

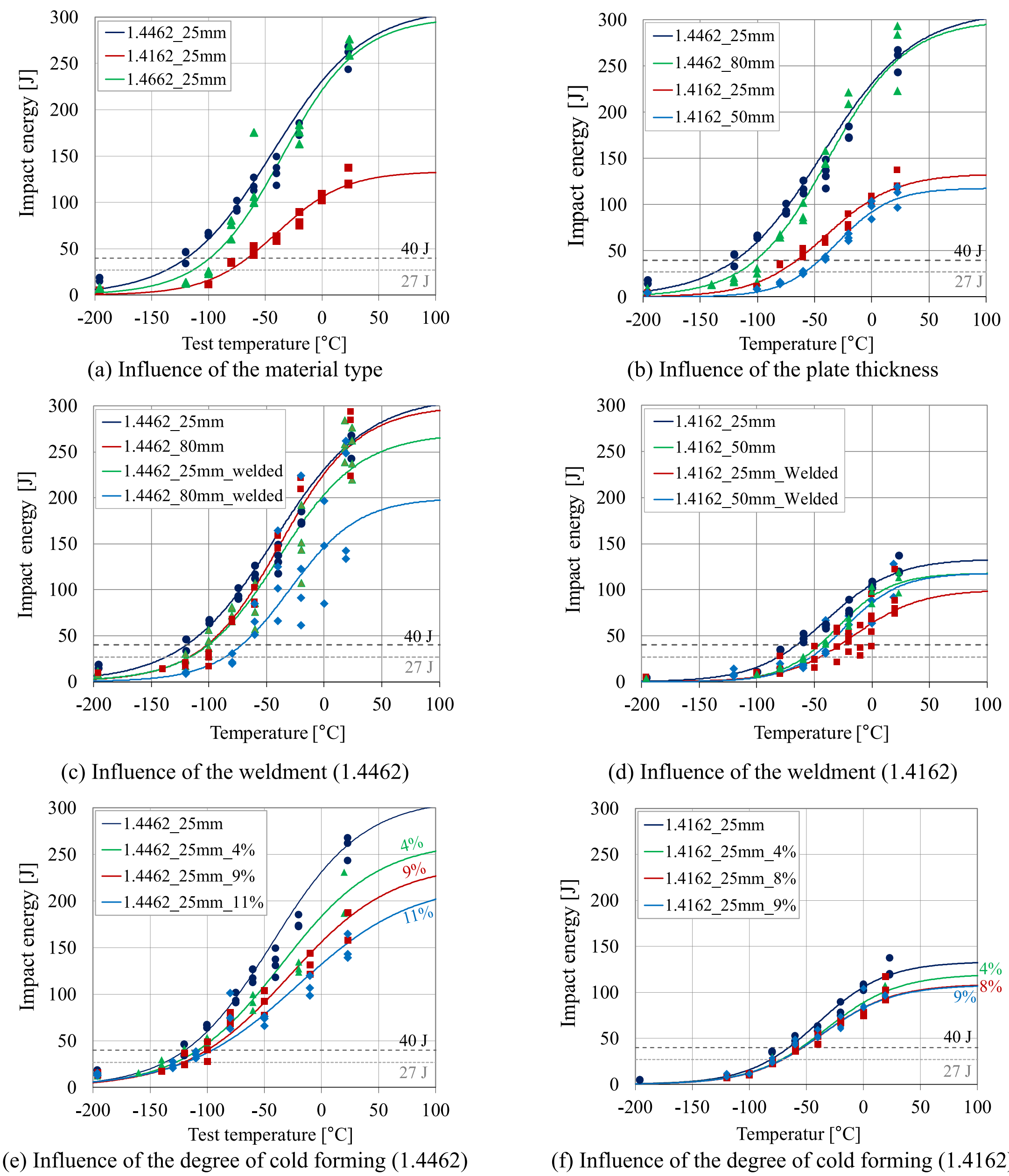
$$\sigma_Y = \frac{\sigma_{YS} + \sigma_{TS}}{2} \tag{6}$$

To achieve the material properties, yield and tensile strength, tensile tests were carried out for 1.4462, 25 mm with standard tensile tests specimens at room temperature. All tensile tests were carried out in a 200 kN servo hydraulic universal testing machine with a video extensometer to measure the specimen elongation according to ISO 6892-1 [36] requirements. Table 4 provides the material properties for 1.4462, 25 mm and 80 mm, 1.4162, 25 mm and 50 mm, and 1.4662, 25 mm as achieved from own tensile tests or as given in the inspection certificates 3.1 acc. to EN 10204 [37]. However, since the tensile properties at low temperatures are essential for the evaluation of fracture toughness test results, the Young's modulus as well as the yield and tensile strength of the material at each fracture toughness testing temperature were obtained by considering the room temperature tensile test results and a cubic polynomial fitted equation based on experimental data presented by Ericsson et al. [24]. J_{IC} was determined by fitting a power law, considering the data points between 0.15 mm and 1.5 mm offset lines parallel to the construction line, see Fig. 5 (c) and (d) and Eq. (5), with C1 and C2 are the power law coefficients. As it is shown in Fig. 5 (c) and (d), J_{IC} was defined as the intersection point between the fitted curve and 0.2 mm crack growth offset to the blunting line (construction line). Regarding the applicability of the Master Curve method (ASTM E1921) to duplex stainless steels, it must be pointed out that defining the critical initiation remains a challenge. The Master Curve method is traditionally designed for materials displaying a clear cleavage initiation, posing an inherent difficulty when applied to materials like duplex stainless steels, which do not undergo a fully cleaved fracture mechanism when the temperature decreases. For this reason, it is a challenge to define a precise critical initiation criterion for these materials. Having SEM (Scanning Electron Microscope) images would help to visually demonstrate semi brittle fracture despite the stable J-R curve, particularly in the context of the 0.2 mm crack extension offset criterion. This analysis is scheduled to be conducted in the near future. However, some studies (like [22]) show that the 0.2 mm crack growth offset to the blunting line, although not synonymous with the critical initiation, proves to be a suitable and consistent criterion. ESIS P1–92 [38], which pertains to the assessment of fracture resistance in ductile materials, also endorses this criterion. This criterion correlates well with prior fracture events, effectively capturing the fracture behaviour in duplex stainless steels. By considering the discussed points and arguments, K_{JC} was calculated based on Eq. (6), where E is Young's modulus of duplex stainless steel at test temperature and $\nu = 0.3$ is Poisson's ratio.

$$K_{JC} = \sqrt{\frac{EJ_{IC}}{(1-\vartheta^2)}} \tag{8}$$

All fracture toughness test results are presented in Table 5. The results show the direct influence of the temperature on the fracture toughness of the material, as with decreasing testing temperature, the fracture toughness decreases as well, see Table 5. Furthermore, from this table, it can be observed that the plate thickness has a noticeable influence on the fracture toughness of the material, too. The fracture toughness results for the higher plate thickness are lower.

The results also show that the highest fracture toughness values were



(a) Influence of the material type

(b) Influence of the plate thickness

(c) Influence of the weldment (1.4462)

(d) Influence of the weldment (1.4162)

(e) Influence of the degree of cold forming (1.4462)

(f) Influence of the degree of cold forming (1.4162)

Fig. 3. Impact toughness transition curves based of experimental tests.

achieved for duplex 1.4462 base material with a thickness of 25 mm because of its high nickel content in comparison to the other lean duplex materials. The specimens made from the thicker plates show lower fracture toughness values for both duplex 1.4462 and lean duplex 1.4162. The results obtained for the welded duplex material 1.4662 show significantly lower fracture toughness in comparison to the base material.

One of the objectives of this contribution was to prove the applicability of the existing correlation between T_{27J} and $T_{100,exp}$ and the validity of the Master Curve concept for duplex stainless steels. Different studies started to check the applicability of these concepts, see [5,24,39]. As the experimental investigations in this project are ongoing and not finalized yet, in the frame of this study, the available results up to the point of preparing this contribution were used for this validity check. The $T_{100,exp}$-temperature was calculated based on the fracture toughness tests for all test series, see Table 5. The relationship between the transition temperature T_{27J} resulting from Charpy-V impact toughness tests and $T_{100,exp}$ is presented in Fig. 6 (a) for the different investigated test series. The results are added to the transition temperature correlation diagram according to EN 1993-1-10 in the range limited by the lower and upper bounds considering a two-time standard deviation ($\sigma = 13$ °C), see Eq. (1). By adding the evaluated results, it becomes obvious that for all test series, these values vary in the presented range. By calculating the standard deviation based on the actual results for the base material of the different duplex stainless steel grades, the standard deviation shows a rather small value of $\sigma = 12$ °C. Based on this observation, it can be concluded that the transition temperature correlation according to Eq. (1) is applicable to the investigated duplex stainless steels.

In the frame of this investigation, the results were evaluated according to ASTM E1921 [40] and analyzed with regard to the Master Curve concept. The Master Curve concept was originally developed for carbon steels [21] and the validity of this concept shall be checked for duplex stainless steels. The aim of this analysis was to observe the scatter of the actual individual fracture toughness test results (K_{JC}) to check the validity of the Master Curve expressed by Eq. (2) for all fracture

Table 3
Transition temperature T_{27J} and T_{40J} for different test series.

Material	Plate thickness [mm]	Base material/ HAZ [1]	Degree of cold forming [%]	T_{27J} [°C]	T_{40J} [°C]	$\Delta T_{\varepsilon cf}$ [2]/ε_{cf} [3] [°C/ %]
1.4462	25	Base material	–	−137	−119	–
	25	HAZ	–	−116	−101	–
	25	Base material	4%	−127	−108	−2.8
	25	Base material	9%	−121	−100	−2.1
	25	Base material	11%	−119	−96	−2.1
	80	Base material	–	−115	−100	–
	80	HAZ	–	−86	−72	–
1.4162	25	Base material	–	−81	−65	–
	25	HAZ	–	−45	−28	–
	25	Base material	4%	−72	−55	−2.6
	25	Base material	8%	−71	−53	−1.5
	25	Base material	9%	−71	−53	−1.3
	50	Base material	–	−65	−50	–
	50	HAZ	–	−53	−40	–
1.4662	25	Base material	–	−114	−99	–

[1] Notch was placed in heat-affected zone (HAZ)
[2] Is the adjustment for the degree of cold forming ε_{cf}
[3] Degree of cold forming in percent.

toughness test results.

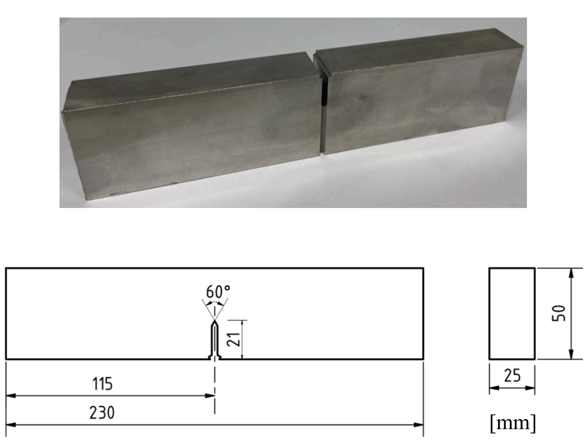
Fig. 6 (b) shows the individual fracture toughness values plotted against the temperature difference between the individual testing temperature (T) and $T_{100,exp}$ (T- $T_{100,exp}$). As mentioned before, $T_{100,exp}$ was calculated for each data set and is presented in Table 5. In Fig. 6 (b), the Master Curves for 5%, 50% and 95% failure probability are presented. It can be seen that all fracture toughness values lay between the upper (95% failure probability) and lower bound (5% failure probability) and are in a good agreement with the presented Master Curve. The outcomes depicted in Fig. 6(b) indirectly validate the Weibull distribution model in accordance with ASTM E1921 for duplex stainless steel, even though it is primarily intended for ferritic steels. As highlighted earlier, in duplex stainless steel, cleavage occurs within the ferrite phase based on a weakest link mechanism, whereby the ferrite phase in duplex stainless steels is a constituent of the austenite-ferrite duplex microstructure. This weakest link mechanism does not result in a complete cleaved fracture but still adheres to the Weibull distribution model.

As expected, the scattering of the results for the weldments is more pronounced since it is difficult to have the notch and the fatigue crack exactly in the heat affected zone and the material in the weldment is more inhomogeneous in comparison to the base material. However, the results obtained for the welded materials fit quiet well with presented Master Curve and they are closer to the upper and lower bound of the Master Curve.

4. Conclusions

In the frame of a German research project, a comprehensive investigation has been started to verify the applicability of the fracture mechanics based concept to avoid brittle fracture for ferritic carbon steels in EN 1993-1-10 to duplex stainless steels. In this paper, first results are presented based on Charpy-V impact and fracture toughness tests. A total of 371 Charpy-V impact tests on three different types of duplex stainless steel were performed. The highest impact toughness was achieved for 1.4462 following by the results achieved for lean duplex 1.4662 and 1.4162. This behaviour confirms that the higher nickel content has a great influence on the toughness of the material. However, lean duplex toughness is still on a sufficiently high level concerning upper shelf toughness and transition temperature. Furthermore, the results show that for the larger plate thickness investigated, the impact toughness is lower and the transition is shifted to higher temperatures. Furthermore, it can be seen that the HAZ in the weldment of both 1.4462 and 1.4162 shows lower impact toughness. An effect that was expected and is known from ferritic carbon steels, too. The question was if the degradation from a commercially performed weld remains within the requirements drawn from the EN 1993-1-10 concept. This question will be answered with the finalisation of the research project. Another factor that affects the impact toughness is the degree of cold forming in the material. A higher percentage of cold forming reduces the toughness of the material. EN 1993-1-10 suggests a 3 °C temperature shift per percent of cold deformation for carbon steel. From the results in this study, this assumption seems to be conservative but acceptable for both duplex 1.4462 and lea duplex 1.4162 stainless steels.

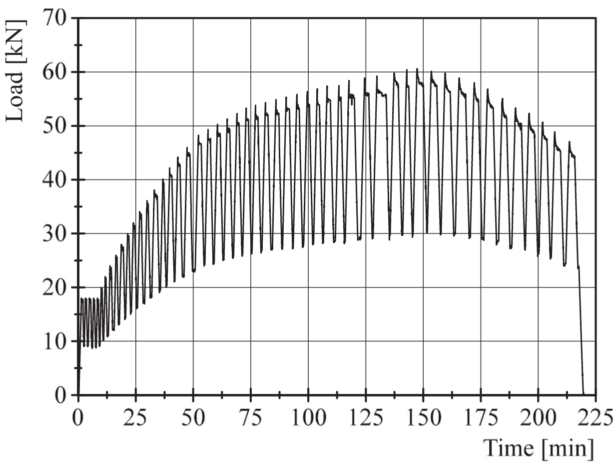
A total of 22 fracture toughness tests were performed so far for three different duplex stainless steels in different thicknesses. As it was expected, the results show that a drop in the testing temperature has a negative influence on the fracture toughness of the material. The results so far obtained show that the plate thickness plays an important role regarding the fracture toughness behaviour of the material, as already known for carbon steel. Lower fracture toughness values are achieved



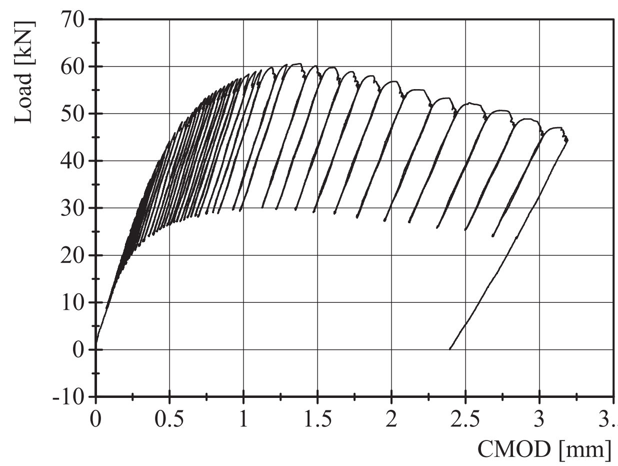
(a) Test specimen geometry


(b) Test setup

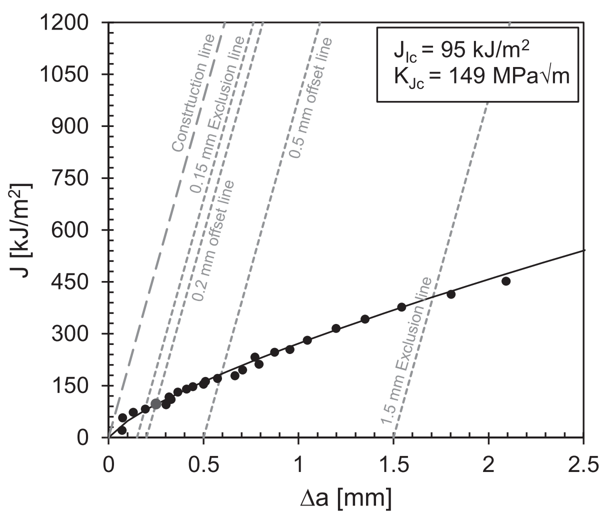
Fig. 4. SENB fracture toughness test specimen geometry according to ASTM E1820 and test setup.



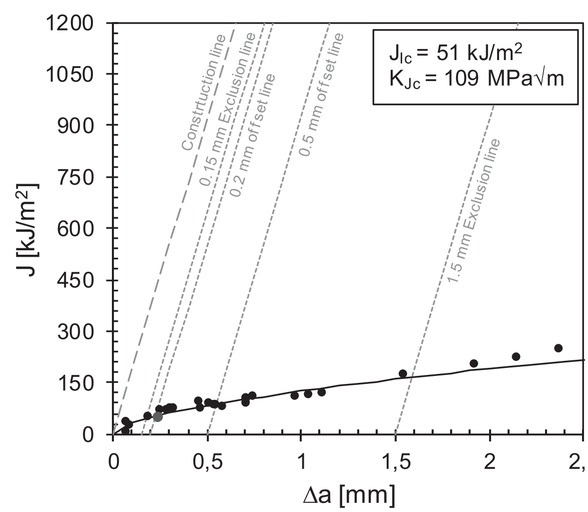
(a) Loading/unloading cycles, Load-time diagram



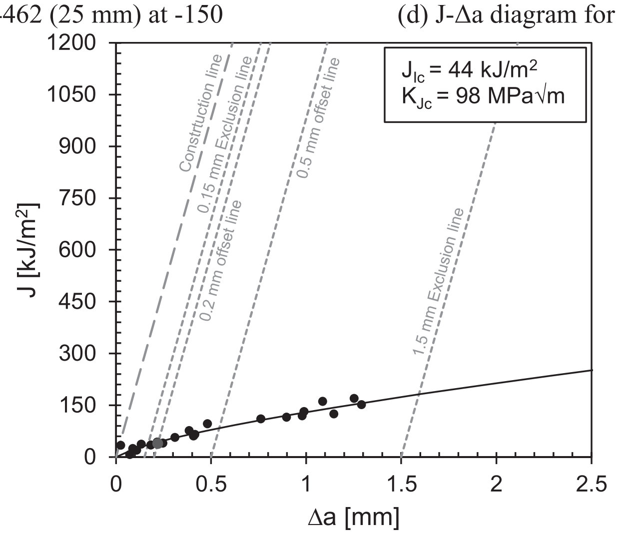
(b) Load-CMOD diagram



(c) J-Δa diagram for 1.4462 (25 mm) at -150



(d) J-Δa diagram for 1.4462 (80 mm) at -150



(e) J-Δa diagram for 1.4462 (25 mm, welded) at -150

Fig. 5. Exemplary loading programme and J-Δa diagram for duplex 1.4462.

for the specimens fabricated from thicker plates for both duplex 1.4462 and lean duplex 1.4162. The results obtained from welded 1.4462 stainless steel plates show lower fracture toughness values for the heat affected zone in compared to the base material.

The achieved test results show that the transition temperature correlation according to EN 1993-1-10 is applicable to the investigated duplex stainless steels. Furthermore, the Master Curve approach presented in ASTM E1921 which was developed for carbon steel material is also valid for the tested duplex stainless steels.

Table 4
Material properties for duplex stainless steels from tensile tests and inspection certificates 3.1.

$$J = C_1\left(\frac{\Delta a}{k}\right)^{C_2} \tag{7}$$

Material	Plate thickness [mm]	Yield strength acc. to the inspection certificate 3.1 [MPa]	Tensile strength acc. to the material certificate 3.1 [MPa]
1.4462	25	479	726
	80	536*	745*
1.4162	25	485	713
	50	505*	757*
1.4662	25	539*	765*

* according to inspection certificates 3.1 acc. to EN 10204 [37]

CRediT authorship contribution statement

Nariman Afzali: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Visualization, Supervision, Project administration. **Georjina Jabour:** Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data curation. **Natalie Stranghöner:** Conceptualization, Methodology, Validation, Writing – review & editing, Supervision, Project administration. **Peter Langenberg:** Conceptualization, Methodology, Validation, Writing – review & editing.

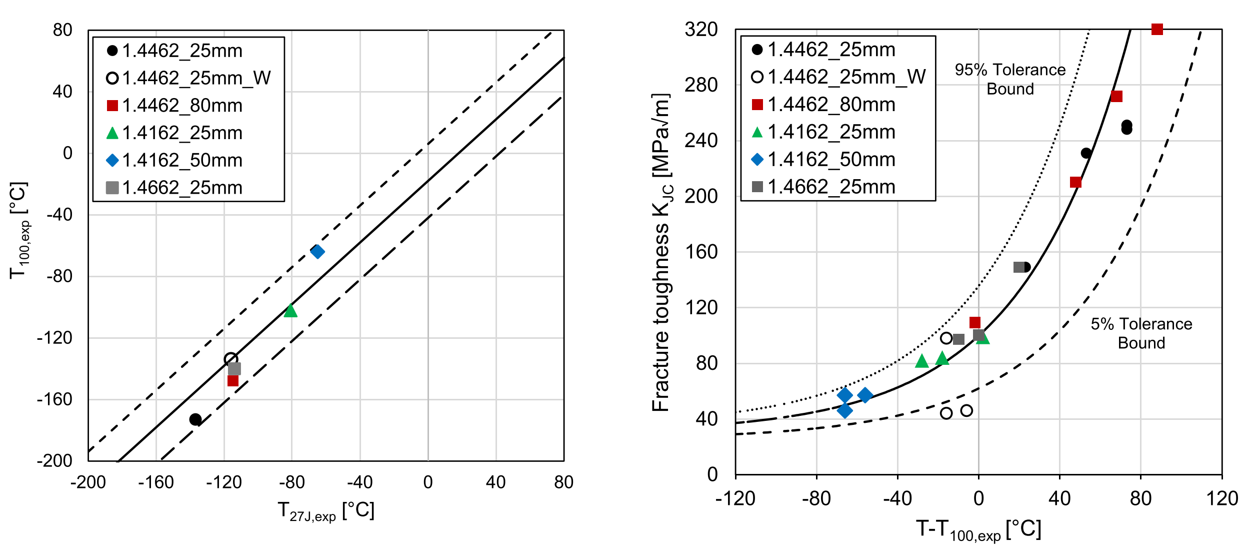
Declaration of Competing Interest

None.

Table 5
Fracture toughness test result.

Material	Plate thickness [mm]	Base material/HAZ [1]	Temperature [°C]	J_{IC} [kJ/mm²]	K_{JC} [MPa$\sqrt{m}$]	$T_{100,exp}$ [°C]
1.4462	25	Base material	−100	272	251	−173
			−100	266	248	
			−120	230	231	
			−150	95	149	
		HAZ	−140	10	46	−126
			−150	9	44	
			−150	44	98	
	80	Base material	−20	1510	584	−148
			−40	1089	497	
			−60	449	320	
			−80	322	272	
			−100	190	210	
			−150	51	109	
1.4162	25	Base material	−100	42	99	−102
			−120	30	84	
			−130	29	82	
	50	Base material	−120	14	57	−64
			−130	9	46	
			−130	14	57	
1.4662	25	Base material	−120	96	149	−140
			−140	43	100	
			−150	40	97	

[1] Notch was placed in heat-affected zone (HAZ).



(a) Correlation between $T_{100,exp}$ und T_{27J} (b) Master Curve concept

Fig. 6. Transition temperature correlation and Master Curve.

Data availability

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