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Global Approach on the Shear and Cross Tension Strength of Resistance Spot Welded Thin Steel Sheets

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Abstract
Several correlations from the professional literature describing the shear and cross tension strength (STS and CTS) of resistance spot welded (RSWed) thin steel sheets were investigated. Some of them need chemical composition or weld nuggets strength hardness as input parameters, making them hardly applicable in the planning stage of the joints. Using STS and CTS data collected from over 250 papers, selected correlations were tested, whether they are applicable to predict the STS and CTS of the RSWed joints at the planning stage to help designers plan their static-loaded welds strength. Most correlations had limitations in the applicable base materials' tensile strength range. Therefore, new equations for STS and CTS are proposed, which can be used to plan in the 300–18900 MPa base metals tensile strength range for similar and dissimilar RSWed joints of thin steel sheets.

Keywords
resistance spot welding (RSW), thin steel sheet, shear tension strength (STS), cross tension strength (CTS)

1 Introduction

Resistance spot welding (RSW) is a prevalent technology for fast joining thin metal sheets. Due to the versatility of the process, it is applicable for various materials from aluminum, copper, or nickel-based alloys and different steel types and material combinations. Depending on the material combinations to be joined, the weldable sheet thickness ranges from thin foils to several millimeter-thick sheets [1].

The most prominent usage of RSW is in the automobile industry, where primarily thin steel sheets need to be welded in various thickness and strength combinations. Thus, different car body parts need different material properties and therefore different steel types. In the automobile industry, there is also a strong strive to save the self-weight of the vehicle to reduce fuel consumption, thus, higher and higher strength steels are used, and need to be welded [2–4]. With the increasing trend towards electric vehicles however, the usage of high strength steels is more pronounced, to compensate the high weight of the battery pack and improve safety and drive dynamics. Therefore, the usage of advanced high-strength steels (AHSSs) or ultra-high-strength steels (UHSSs) is nowadays pretty common in car bodies. Of course, this striving to reduce self-weight and use high-strength steels is also present in many different industry branches [5–8].

To produce sound parts high quality spot welds are needed. There are a lot of standardized and non-standardized testing methods to qualify and quantify the soundness of the joints, like shear tension, cross tension, coach peel, fatigue, and also different dynamic tests [1].

For design purposes at least some strength values should be estimated beforehand. Therefore, in our work we try to find some prediction models to estimate the shear tension strength (STS) and the cross tension strength (CTS) for static-loaded joints to help designers at the planning stage of the RSWed joints.

2 Literature research

There are lots of works in the literature for RSW of steel, where the different mechanical properties of the joint were investigated. Some correlations were found between the properties of base materials or weld materials (e.g., hardness, tensile strength etc.) and the different joint strength types (e.g., STS, CTS, coach peel strength, etc.). Most are developed for a narrow range of steel types in thickness,

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chemical composition, or tensile strength. Those empirical correlations for STS and CTS will be investigated here to determine whether they are applicable in the planning stage of RSWed joints strength if only the desired base material strength and the thickness is known.

2.1 Prediction of the shear tension strength

In the literature, there are several types of research to predict the achievable STS of the RSWed steel joints.

Heuschkel [9] investigated more than 4000 RSWed joints of manganese alloyed plain carbon steels in different sheet thicknesses. He made a mathematic model for predicting the STS Eq. (1)[1],

$$\mathrm{STS}(\mathrm{lb}) = t \cdot d \cdot R_m \cdot \left(\alpha - \beta \cdot (\mathrm{C} + 0.05 \cdot \mathrm{Mn})\right) \tag{1}$$

where t is the sheet thickness (here in inch), d is the weld nugget diameter (here in inch), R_m is the base materials tensile strength (here in psi), α (1.5–3.5), and β (0.5–4.5) (depending on the sheet thickness) are components of shear tension strength formulas without dimension and C, Mn are the carbon and manganese content in mass %. The correlation worked well in the investigated R_m range 320–880 MPa and sheet thickness (0.2–12.7 mm) and chemical compositions in the range of $0.01 < \mathrm{C}\% < 0.58$ and $0.29 < \mathrm{Mn}\% < 0.87$. But obviously, previous knowledge of chemical composition is needed to be able to use this function.

Sawhill and Baker [10] found a simple equation (Eq. (2)) for re-phosphorized steel for a low R_m range (350–550 MPa),

$$\mathrm{STS} = A \cdot t \cdot d \cdot R_m \tag{2}$$

where A is a coefficient. It was determined A = 3, and for low carbon equivalents A = 2.5–3.0. This equation would be a simple tool if there were a narrow range of coefficient A for all steel compositions.

Defourny et al. [11] investigated 1–2 mm thick mild steel and high strength low alloy steel (HSLA) and developed their correlation for STS (Eq. (3)). This correlation is promising and thus does not consider the chemical composition, only the base metals' strength and sheet thickness.

$$\mathrm{STS}(\mathrm{daN}) = 9.5 \cdot t^{1.26} \cdot {R_m}^{0.76} \tag{3}$$

Many researchers compared the different type of joint failure under shear-tensile load. For shear type or interfacial fracture e.g., [12, 13] (Eq. (4) and Eq. (5)), [14] (Eq. (6)), and [15] (Eq. (7)),

$$\mathrm{STS} = B \cdot 2\big/\sqrt{3} \cdot \pi \cdot d^2\big/4 \cdot R_{m\ \mathrm{nugget}} \tag{4}$$

$$\mathrm{STS} = 9.8 \cdot \pi \cdot d^2\big/4 \cdot HV_{\mathrm{nugget}}\big/3^{1.5} \tag{5}$$

$$\mathrm{STS} = D \cdot d^2 \cdot R_m \tag{6}$$

$$\mathrm{STS}(\mathrm{daN}) = 1.1 \cdot d^2 \cdot HV_{\mathrm{nugget}} \tag{7}$$

where $R_{m\ \mathrm{nugget}}$ and HV_{nugget} are the weld nuggets tensile strength and Vickers hardness, respectively. B and D are coefficients $D \sim 0.6$. In most engineering applications, interfacial fracture of the weld nugget is to be avoided. Therefore, these correlations were not investigated in detail. Another difficulty with Eqs. (4)–(6) is that $R_{m\ \mathrm{nugget}}$ and HV_{nugget} are measurable but hardly predictable in the planning stage. Some models are developed for their prediction (e.g., [16–21]), mostly based on the chemical composition of the base material, but their usage is limited to selected steel groups.

Kuo and Chiang [22] investigated steel grades in 400 MPa $< R_m <$ 1000 MPa strength range, and for interfacial fracture they proposed a correlation; where STS is proportional with the weld nugget size, the hardness ratio between nugget and base material ($\mathrm{Hard.} = HV_{\mathrm{nugget}} / HV_{\mathrm{BM}}$) and the shear strength of the base material (Eq. (8)).

$$\mathrm{STS} = \mathrm{Hard.} \cdot d^2\big/4 \cdot \tau_m = HV_{\mathrm{nugget}}\big/HV_{\mathrm{BM}} \cdot d^2\big/4 \cdot \tau_m \tag{8}$$

Where HV_{BM} is the base materials Vickers hardness and τ_m is the shear strength of the base material.

Of course, as mentioned earlier the favorable failure type for most engineering applications under shear load is the plug type or pull-out fracture, there are several equations for that as well.

Oikawa et al. [12, 13] found the same equation as Eq. (2) to be applicable and other correlations too (Eqs. (9)–(12)).

$$\mathrm{STS} = E \cdot t \cdot d_{\mathrm{plug}} \cdot R_m \tag{9}$$

$$\mathrm{STS} = F \cdot t^{1.26} \cdot {R_m}^{0.76} \tag{10}$$

$$\mathrm{STS} = 36.4 \cdot t^{1.42} \cdot {R_m}^{0.84} \tag{11}$$

$$\mathrm{STS}(\mathrm{kN}) = 2.05 \cdot t \cdot R_m \cdot (d + 2.09) \cdot (1 + 0.0059 \cdot \mathrm{El.}) \tag{12}$$

Where E, F are coefficients, d_{plug} is the diameter of the pulled-out plug after pull-out fracture, and El. is the elongation of the base metal sheets. The diameter of the plug is measurable, but the prediction is hardly applicable. Also, the elongation of the selected steel group is might not been known in the planning stage of the welded part, therefore Eq. (9) and Eq. (12) will not be investigated further.

1 Note for the other formulas if not indicated otherwise SI units are used STS is given in N, t and d in mm, R_m in MPa.

Equation (10) and Eq. (11) donot consider the weld nugget size, but they could be easy to use for planning.

Sakuma and Oikawa [23] and Sakuma et al. [24] also proposed a correlation for STS either from the weld nugget strength and size (Eq. (13)),

$$\mathrm{STS} = G \cdot \pi \cdot d^2 / 4 \cdot R_{m\ \mathrm{nugget}} \tag{13}$$

where G is a constant. The investigated steels were in the $R_m = 400–800$ MPa strength range and $t = 1–2.6$ mm thick. Again, the weld nuggets strength is hard to forecast, therefore this correlation is hardly applicable in the planning stage. They also investigated Eq. (2) and determined factor $A = 2.5–3.3$, and found it is also dependent on the sheet thickness, base materials' strength, and the chemical composition mainly the carbon and silicon content, which makes the application of a relatively simple correlation a lot more complicated.

Radakovic and Tumuluru [14] and Tumuluru [25] investigated the spot welds strength of various steel types (interstitial free (IF), dual phase (DP), and transformation induced plasticity (TRIP) steels) in the $R_m = 300 – 880$ MPa strength range in $t = 1–1.6$ mm thicknesses. They found for pull-out fracture mode Eq. (2) to be sound with $A = 2.2–2.25$.

There are of course, standardized correlations for the minimum acceptable STS for uncoated and coated low carbon steels, e.g., International Organization for Standardization (ISO) and British standards (BS). Both the ISO 14373:2015 [26] and the BS 1140:1993 [27] standard requires a minimum STS according to Eq. (2) where $A = 2.6$. The BS 1140:1993 standard [27] also gives correlations for dissimilar joints according to Eqs. (14)–(16),

$$\text{if} \quad t_1 < t_2 < 2.5 \cdot t_1 \quad \mathrm{STS} = 2.7 \cdot \sqrt{t_1} \cdot d \cdot R_{m1} \tag{14}$$

$$\text{if} \quad t_2 > 2.5 \cdot t_1 \quad \mathrm{STS} < 0.691 \cdot d^2 \cdot R_{m1} \tag{15}$$

$$\text{if} \quad t_2 > 2.5 \cdot t_1 \quad \mathrm{STS} < 3.08 \cdot t_1 \cdot d \cdot R_{m1} \tag{16}$$

where t_1, t_2 are the thicknesses and R_{m1}, R_{m2} are the tensile strength of the steel sheets.

These listed equations (Eqs. (1)–(16)) give their correlation mostly in the $R_m < 900$ MPa strength range, but the newly developed AHSS and UHSS grades can have more than two times this tensile strength. The AWS D8.1M:2013 standard [28] made for automotive applications fills this gap and gives a correlation for the minimum acceptable STS (Eq. (17)). Equation (17) already covers the whole strength range from normal strength steels till AHSSs. There is one interesting property though, namely above 1340 MPa R_m the required STS values start to decrease.

$$\mathrm{STS} = \left(-6.36 \cdot 10^{-7} \cdot R_m^2 + 6.58 \cdot 10^{-4} \cdot R_m + 1.674\right) \cdot R_m \cdot 4 \cdot t^{1.5} \tag{17}$$

Previously the authors [29] analyzed STS data from approx. 80 papers in the professional literature, and found, that this decrement in the STS values in the UHSS range is not necessarily right (at least not that severe) and proposed a new correlation above 1340 MPa base materials tensile strength (Eq. (18)).

$$\mathrm{STS} = \left[3788.77 - \begin{pmatrix} -6.36 \cdot 10^{-7} R_m^2 \\ +6.58 \cdot 10^{-4} \cdot R_m \\ +1.674 \end{pmatrix} \cdot R_m \right] \cdot 4 \cdot t^{1.5} \tag{18}$$

This was a basic concept, which increased the STS values of the AWS D8.1M:2013 standard [28] with the same amount as it was below its maxima (at $R_m = 1340$ MPa). After extended literature and experimental research, data of approx. 160 papers were analyzed [30] and a prediction for the STS values was given in a wide tensile strength range ($R_m = 400–2000$ MPa), for thin steel sheets ($t = 0.3–4$ mm) (Eq. (19)). This correlation suggests that STS keeps increasing in the whole R_m range even if $R_m > 1340$ MPa. The comparison between the Eq. (1) according to Radakovic and Tumuluru [14] and Tumuluru [25], according to the ISO standard [26] and the Eq. (18) according to the AWS standard [28] was also presented here [30].

$$\mathrm{STS(kN)} = -10.10 + 15.80 \cdot t + 0.0088 \cdot R_m \tag{19}$$

Xu et al. [31, 32] conducted many experiments in a wide tensile strength range of $R_m = 250–1600$ MPa steel, $t = 0.6–1.6$ mm thickness in similar and dissimilar combinations. They made a standardized shear strength function which multiplied with the sheet thicknesses (Eq. (20)) gave a good correlation with their experimentally measured STS values. According to this function (Eq. (20)), STS monotonously increases in the UHSS range too:

$$\mathrm{STS} = t_1 \cdot t_2 \cdot \begin{pmatrix} 8 \cdot 10^{-9} \cdot R_{m1}^3 - 3 \cdot 10^{-5} \cdot R_{m1}^2 \\ +0.0418 \cdot R_{m1} - 6.0904 \end{pmatrix}, \tag{20}$$

where $R_{m1} < R_{m2}$. Note that besides the Eqs. (14)–(16) of the BS 1140:1993 standard [27] this is the only correlation easily applicable for dissimilar joints. While, the British standard relies on the thinner sheet thickness, Eq. (20) relies on the weaker base material of the two sides of the weld.

Of course, the other equations also can be used for dissimilar welds. Here, it is recommended to calculate the

STS according to both sides of the joint and use the smaller value for designing the welded part.

2.2 Prediction of the cross tension strength

To prepare cross tension specimen and measure their strength is a little bit more complicated, maybe that's why there are fewer formulas to forecast the cross tension strength of RSWed joints, than for STS.

Heuschkel [9] also investigated the CTS of the carbon and manganese alloyed steels (Eq. (21))[2].

$$\mathrm{CTS(lb)} = t \cdot d \cdot R_m \cdot \left[a/(R_m - b) + c - (f \cdot \mathrm{C} + g \cdot \mathrm{Mn}) \right] \quad (21)$$

Where t is the sheet thickness (here in inch), d is the weld nugget diameter (here in inch), R_m is the base materials tensile strength (here in psi), a and b components of normal strength formulas in psi, c, f and g components of normal strength formulas without dimension and C, Mn are the carbon and manganese content in mass %. The problem here is the same, as with their STS formula (Eq. (1)), namely previous knowledge of chemical composition is needed to be able to use this function, and its limited R_m and chemical composition range.

There are other formulas from Oikawa et al. [12, 13] for shear type fracture based on the weld nuggets' mechanical properties (hardness and tensile strength) (Eq. (22) and Eq. (23)),

$$\mathrm{CTS} = H \cdot \pi \cdot d^2/4 \cdot R_{m\ \mathrm{nugget}} \quad (22)$$

$$\mathrm{CTS} = 9.8 \cdot \pi \cdot d^2/4 \cdot (1.4 - 0.003 \cdot HV_{\mathrm{nugget}}) \cdot (HV_{\mathrm{nugget}}/3) \quad (23)$$

where H is a coefficient.

Kuo and Chiang [22] proposed for interfacial fracture too, to use the hardness ratio in their equation (Eq. (24)).

$$\mathrm{CTS} = \mathrm{Hard.} \cdot \pi \cdot d^2/4 \cdot R_m = HV_{\mathrm{nugget}}/HV_{\mathrm{BM}} \cdot \pi \cdot d^2/4 \cdot R_m \quad (24)$$

Equations (22)–(24) are hard to use thus as already mentioned the weld metals' hardness and tensile strength are hard to predict in the planning stage. Of course, in the case of the cross tension (normal) load, the favored fracture type is the pull-out fracture. Therefore, these correlations were not investigated in detail.

For the preferred pull-out fracture Oikawa et al. [12, 13] proposed Eqs. (25)–(27)). In the planning stage Eq. (26) is the handiest, thus only the sheet thickness and nugget size is needed.

$$\mathrm{CTS} = I \cdot 2/\sqrt{3} \cdot \pi \cdot t \cdot d \cdot R_{m\ \mathrm{nugget}} \quad (25)$$

$$\mathrm{CTS} = 645 \cdot t \cdot d^{1.27} \quad (26)$$

$$\mathrm{CTS} = 5 \cdot \pi \cdot t \cdot d \cdot R_{m\ \mathrm{nugget}} \cdot \left[1 - 100/(100 + 0.5 \cdot \mathrm{El.})\right]^{1.46} \quad (27)$$

Sakuma and Oikawa [23] and Sakuma et al. [24] proposed a similar correlation (Eq. (28)) for the CTS as Eq. (2) for the STS values.

$$\mathrm{CTS} = J \cdot t \cdot d \cdot R_m \quad (28)$$

Where J is a coefficient. The investigated steels were in the 400 MPa < R_m < 800 MPa strength range and t = 1–2.6 mm thickness range. They determined, J = 1.2–2.7 of and found it is dependent on the sheet, thickness, base materials' strength and the chemical composition, mainly the carbon and silicon content.

Kuo and Chiang [22] proposed a correlation for pull-out fracture too. They used the hardness ratio in their equation as well (Eq. (29)).

$$\mathrm{CTS} = \mathrm{Hard.} \cdot \pi \cdot t \cdot d \cdot \tau_m = HV_{\mathrm{nugget}}/HV_{\mathrm{BM}} \cdot \pi \cdot t \cdot d \cdot \tau_m \quad (29)$$

As for the standardized correlations, the AWS D8.1M:2013 standard [28] gives the minimum acceptance criteria for automotive applications for CTS values too (Eq. (30)).

$$\mathrm{CTS} = 1.25 \cdot t^{2.2} \quad (30)$$

Here again, the only parameter is the steel sheets thickness.

The equations for calculating CTS (Eqs. (21)–(30)) also can be used for dissimilar welds, here it is recommended to calculate the CTS according to both sides and use the smaller value for designing the welded part.

2.3 Other possibilities of strength prediction

Naturally, correlations get better and better, the narrower the sheet thickness and material range e.g., Rajarajan et al. [33] predicted very accurately the STS, CTS, HV_{nugget} values of RSWed DP800 steel sheets. Good estimations can be made with numerical [34–38] and finite element (FEM) simulations [39–43], machine learning [44], and artificial neural networks [45–48]. These methods can be a very useful and accurate tools to optimize and predict weld properties (STS and CTS as well), but they are primarily applicable to a specific narrow

2 Note for the other formulas if not indicated otherwise SI units are used CTS is given in N, t and d in mm, R_m in MPa.

application area, not to a wide range of material strength classes and combinations.

Therefore, these methods are used not in the planning stage of the RSWed parts, but more likely in the optimization of the joint and in whilst establishing an applicable parameter window for production and during quality control by monitoring of the manufacturing process.

2.4 Data collection and processing

In the main scientific databases (e.g., Science Direct, Web of Science, J-Stage etc.) keyword-based searches were run to find possible papers with STS or CTS data. Also, complementary searches were made in specifically welding related journals (e.g., Welding in the World, Welding Journal, Quarterly Journal of the Japan Welding Society, Hegesztéstechnika etc.). The keywords were: resistance spot welding, steel and if available the different joint strengths. Papers mostly in English and Hungarian were processed but also in Japanese and Korean if the figures/tables and their captions were presented in English. STS and CTS data were collected if at least the sheet thicknesses and base materials strength could be determined from the manuscript. If available complementary data, like nugget size, absorbed energy, and scatter for those was also collected. To avoid excess and mostly bad data points, only the STS or CTS data were collected, corresponding to an optimized joint (highest STS or CTS).

To investigate the effectiveness of the concrete correlations, the normalized STS or CTS values for the given equations ($STS_{measured}/STS_{equation}$ or $CTS_{measured}/CTS_{equation}$) are calculated in Excel® software. The diagrams were made with Origin® software. In case of the dissimilar joints the STS or CTS values were calculated for both sides for the joints – and if the given correlation did not specify otherwise – the value for the weaker side was used for the calculation of the normalized values. For better visualization of the trends of the different equations linear regression using least squares method was made also with Origin® software on most of the plots.

3 Results and discussion

From the listed correlations (Eqs. (1)–(30)) some are harder some are easier applicable in the design stage of the RSWed parts, STS and CTS data of couple hundred papers was collected and evaluated according to the selected equations to see their feasibility for predicting the STS or CTS values in a wide base metals range.

3.1 Evaluation of the STS correlations

From the listed equations for the STS values (Eqs. (1)–(20)) some could be already used in the design stage for shear-tensile loaded RSWed joints. Of course, interfacial fracture is to be avoided. If the concrete material is not yet known for the part to be welded, only the equations which require tensile strength and thickness (Eqs. (2), (3), (10), (11), (14) and Eq. (20)) can be applied, therefore the literature data for those correlations was evaluated. STS data from more than 240 papers was analyzed. The STS values from the professional literature for the optimized joints are plotted in Fig. 1 [12–17, 23, 25, 29, 31–35, 38–40, 45, 47, 49–273]. The dissimilar joints were depictured as the "weaker side" of the joint according to the requirement (Eq. (17)) of the AWS D8.1M:2013 standard [28].

The measured STS values vs. the sheet thicknesses are plotted on Fig. 2. According to this diagram, the STS values increase significantly with the sheet thickness, but the scatter is really high, e.g., for a steel sheet thickness of 2 mm the measured STS values were between 10–46 kN. After linear fitting the STS values for 2 mm thick sheets are predicted to be in the very wide range of 16–40 kN (95% prediction band). Therefore, the applicability of such equations where the sheet thickness is the only parameter

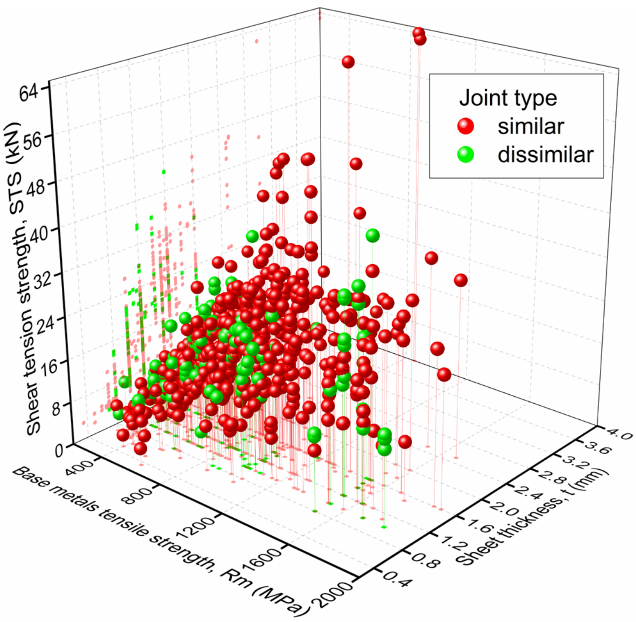

Fig. 1 Graphical representation of the literature data of the STS values is shown in similar [12–17, 25, 29, 31–35, 38, 39, 45, 49–239] and dissimilar [23, 29, 31, 32, 34, 38, 40, 47, 50, 61, 63, 67, 74, 99, 102, 107, 116, 118, 120, 121, 134, 138, 144, 162, 163, 170, 205, 214, 223, 231, 233, 240–273] RSWed joints. For the dissimilar joints, the weaker side is depictured according to Eq. (17).

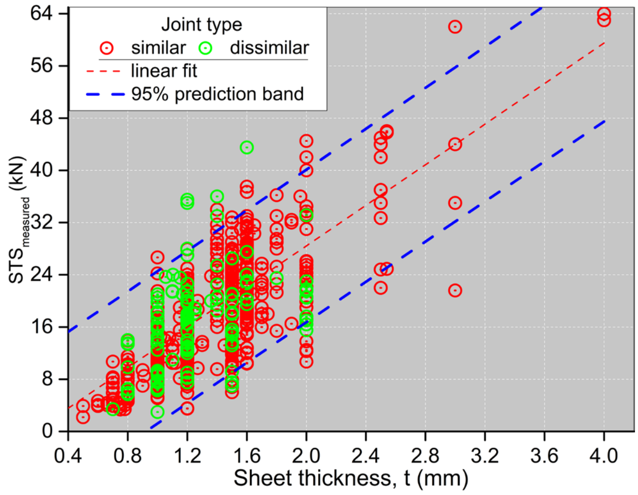

Fig. 2 The measured STS values are shown in similar and dissimilar RSWed joints, for the dissimilar joints, the weaker side is depicptured.

for predicting the STS values beforehand seems to be very limited, but they were investigated, nevertheless.

In Fig. 3 the normalized STS values for Eq. (3) is represented in the whole R_m range of R_m = 300–1900 MPa. The normalized STS values are between ~0.3–1.5 and scatter asymmetrically around the fitted trend line +0.4, and –0.6 at lower R_m and at higher base materials strength it is more pronounced. The normalized STS values are tendentiously decreasing in the whole R_m range. Therefore, Eq. (3) is not recommended for designing the joint strength.

Basically Eq. (10) is very similar to Eq. (3), but in [12, 13] factor F was not presented for Eq. (10). Therefore, a parameters search was made via Origin® software on the similar joints STS data. F = 70.47 was found to be the best fit (with R^2 = 0.55). The normalized STS values for Eq. (10) with F = 70.47 are in Fig. 4 and they are between ~0.4–1.7. This is a bit larger scatter, than in the case of Eq. (3), but the normalized STS values are symmetrically distributed around the fitted line. Moreover, Eq. 10 has the same shortcoming namely, the normalized STS values are tendentiously decreasing in the whole R_m range and above R_m ~ 1200 MPa it goes bellow 1. Practically it means that the correlation for lower strength steels overestimates the achievable STS values and for UHSS R_m > 1200 MPa it underestimates them. Therefore, Eq. 10 is not recommended for designing the joint strength.

Equation (11) takes the sheet thickness and tensile strength of the material with more weight into account ($t^{1.42}$, $R_m^{0.84}$) compared to Eq. (3) or Eq. (10), which results in a larger scatter in the normalized STS values ~0.5–2.5 (Fig. 5). For Eq. (11) too, in the whole base materials tensile Fig. 5 strength range a clear decreasing trend can be observed, and the normalized STS values above R_m ~ 1300 MPa fall below 1. Therefore, Eq. (11) is not recommended for designing the joint strength either.

Normalized STS values for the AWS D8.1M:2013 standard [28] can be seen on Fig. 6. In outmost cases the values are above 1, therefore the correlation fulfills its original purpose as a boundary for minimal acceptable STS values. Applying it to the joint strength's planning nevertheless proves to be difficult.

Because as discussed also in [29, 30], the scatter is high ~1–4, and due to the nature of Eq. (17), the normalized STS values decrease till R_m = 1340 MPa, and then they start to increase again. Therefore, this increment R_m > 1340 MPa is somewhat dampened by Eq. (18).

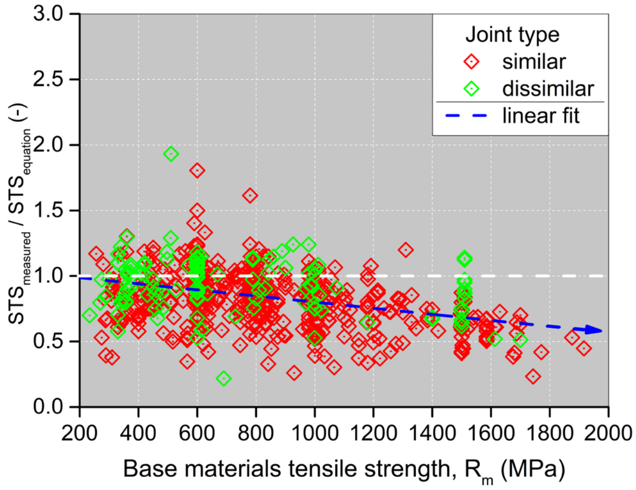

Fig. 3 Normalized STS values are shown according to Eq. (3) for similar and dissimilar RSWed joints, for the dissimilar joints, the weaker side is depictured.

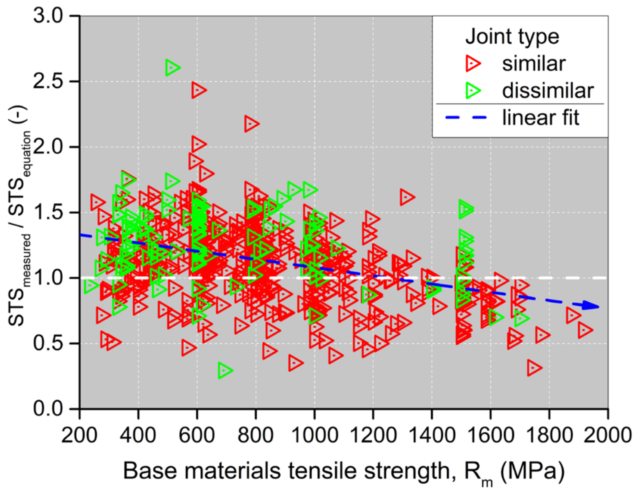

Fig. 4 Normalized STS values are shown according to Eq. (10) with F = 70.47 for similar and dissimilar RSWed joints, for the dissimilar joints, the weaker side is depictured.

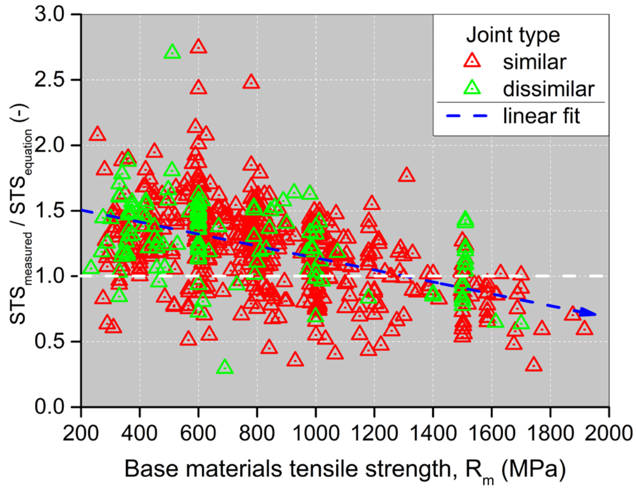

Fig. 5 Normalized STS values are shown accoriding to Eq. (11) for similar and dissimilar RSWed joints, for the dissimilar joints, the weaker side is depictured.

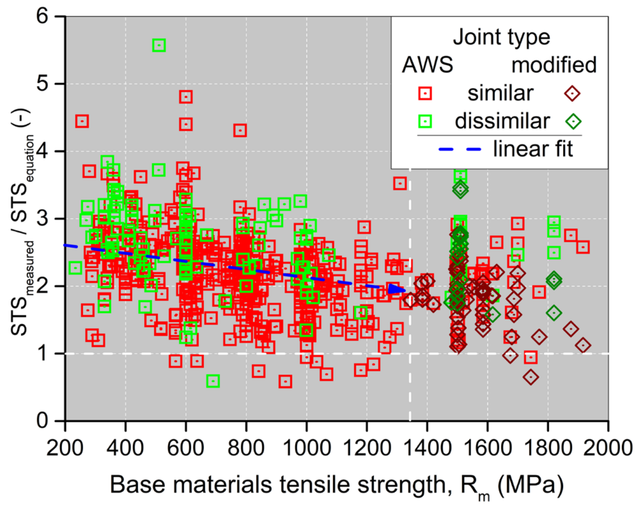

Fig. 6 Normalized STS values are shown according to the AWS standard [28] (Eq. (17)) and modified by the authors [29] when R_m > 1340 MPa (Eq. (18)) for similar and dissimilar RSWed joints. For the dissimilar joints, the weaker side is depictured according to Eq. (17) and Eq. (18).

For these reasons, these equations are not recommended for designing the joints strength.

Equations where the nugget size is also a parameter are tricky to use in the planning for the joint strength, but we present a typical approach. According to the literature and also standards (e.g. [1, 274]) to produce sound RSWed joints the weld nuggets diameter should be at least $3.5 \cdot \sqrt{t}$, because bellow this value different type of weld defects can occur, e.g., lack of fusion, stuck weld etc. The maximum weld nugget size is set typically $5 \cdot \sqrt{t}$ (according to [26]), eventually $6 \cdot \sqrt{t}$, but above this size, other weld defects will occur e.g., splash. Therefore, we will investigate the correlations where d the nugget size also a parameter is, in the typical region $d = 3.5 – 5 \cdot \sqrt{t}$.

Sawhill and Baker's [10] equation (Eq. (2)), is used by various authors and even in standards [14, 25–27]. The normalized STS values for the two extrema ($A = 2.2$, $d = 3.5 \cdot \sqrt{t}$ and $A = 2.6$ and $d = 5 \cdot \sqrt{t}$) are visualized in Fig. 7 and Fig. 8. It is important to mention that the real nugget sizes maybe differ from the ones assumed in the calculation.

In Fig. 7 there are the normalized STS values, for the smallest STS requirement. These values at small R_m (~300 MPa) scatter around ~2.6±1.4, and a clear decreasing trend can be observed, the normalized STS values at R_m ~ 1000 are in the range ~1.7±1. Here in most cases normalized STS values are above 1 (till R_m ~ 1700 MPa), but

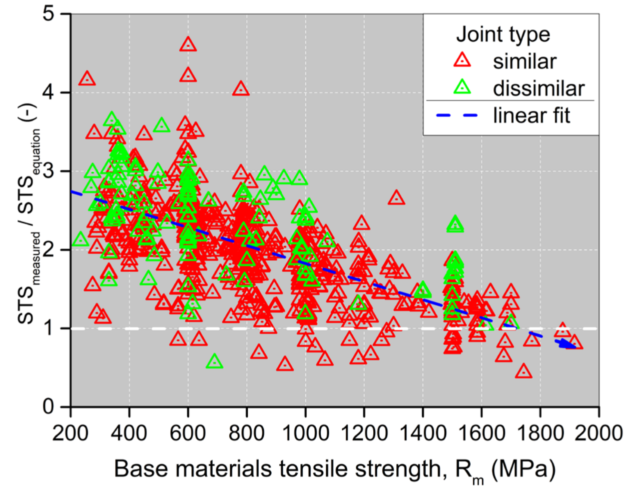

Fig. 7 Normalized STS values are shown according to Eq. (2) where $A = 2.2$ and $d = 3.5 \cdot \sqrt{t}$ for similar and dissimilar RSWed joints. For the dissimilar joints, the weaker side is depictured.

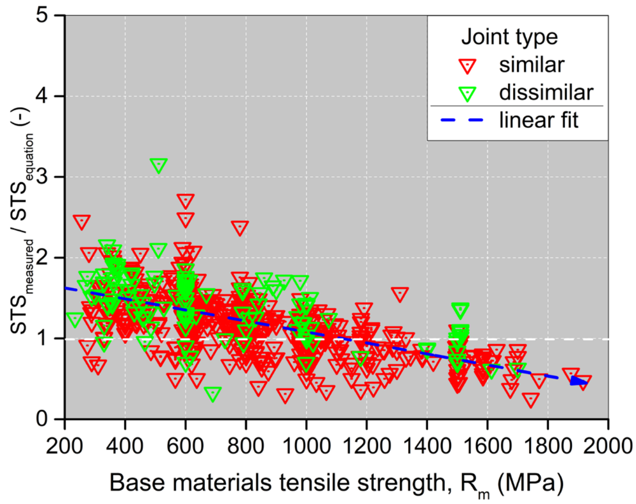

Fig. 8 Normalized STS values are shown according to Eq. (2) where $A = 2.6$ and $d = 5 \cdot \sqrt{t}$ for similar and dissimilar RSWed joints. For the dissimilar joints, the weaker side is depictured.

still more values are below 1 than in the case of Eq. (17) (Fig. 6), therefore as a boundary for minimal acceptable STS values is Eq. (17) a better choice. We have to mention however, that the standardized equation was meant to be used for low carbon steels, and in the UHSS range (R_m > 800 MPa) for most steel types, the carbon content also keeps increasing with higher R_m. Therefore Eq. (2) is only recommended to be used to estimate the minimum acceptable STS values for steels R_m < 800 MPa, where $A = 2.2$ and $d = 3.5 \cdot \sqrt{t}$, and d is not the actual (measured) nugget size it is only for the calculation.

In Fig. 8 there are the normalized STS values (for the larger STS requirement). If the actual nugget size is not known, $d = 5 \cdot \sqrt{t}$ was used to calculate the minimum acceptable STS of the steels. In the whole R_m range similar decreasing trend can be observed than in Fig. 7. The normalized STS values scatter at low R_m (~ 300 MPa) around 1.5±0.9 but at ~R_m = 1200 MPa these values go below 1. Therefore, for the planning of the joint strength Eq. (2) is not recommended either.

However, in case of similar joints, the British standard [27] uses the same equation as the ISO standard [26], the British standard also gives correlations for the dissimilar joints using the mechanical properties of the thinner side of the joint (Eq. (15) and Eq. (16)). As we can see in Fig. 9 the British Standard gives a little bit smaller normalized STS values in the whole R_m range than the ISO standard. The same decreasing trends can be observed, but the slope of the decrement is smaller in the case of the ISO standard.

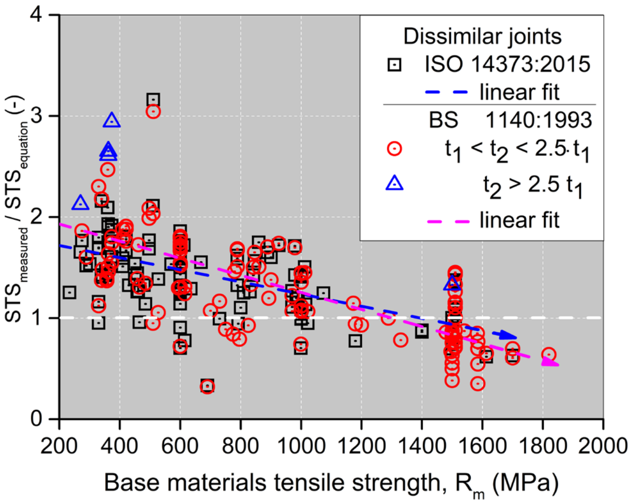

Fig. 9 Normalized STS values of the dissimilar RSWed joints are shown according to the ISO 14373:2015 standard [26], where $A = 2.6$ and $d = 5 \cdot \sqrt{t}$ are used by Eq. (2), and the weaker side is depictured. Normalized STS values of the dissimilar RSWed joints are shown according to the BS 1140:1993 standard [27], where $d = 5 \cdot \sqrt{t}$ is used by Eq. (15) and Eq. (16), and the weaker side is depictured.

The normalized STS results of Xu et al. [31, 32] approach (Eq. (20)) using the smaller R_m of the two base materials is visualized in Fig. 10. The normalized values are mostly in ~0.3–1.5 range, at lower tensile strength it's a bit more (~0.3–2.0). Overall, the normalized STS values scatter around ~0.9±0.6 and no significant decreasing trend can be observed. Therefore, with a safety factor ~3 this correlation could be used globally to predict the STS values.

Previously [30] a plane was fitted on the optimized STS values (similar joints) depending on the base materials' tensile strength and sheet thickness (Eq. (19)). This was done based on STS data of approx. 160 papers. Again, plane fitting was done, but now based on data of over 200 papers (Fig. 11, Eq. (31)). Small refinement was made

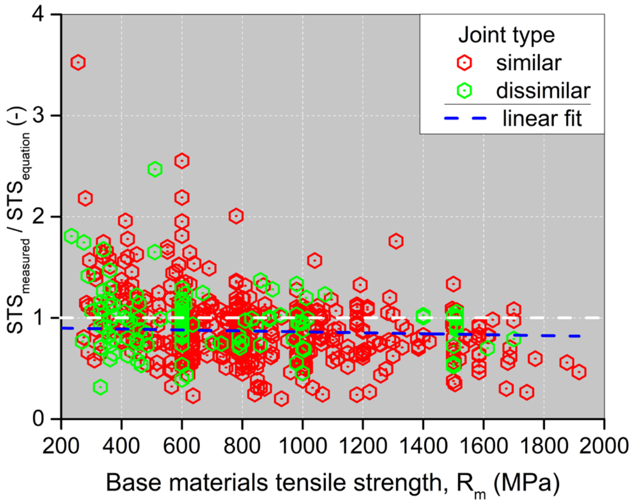

Fig. 10 Normalized STS values are shown according to Eq. (20).

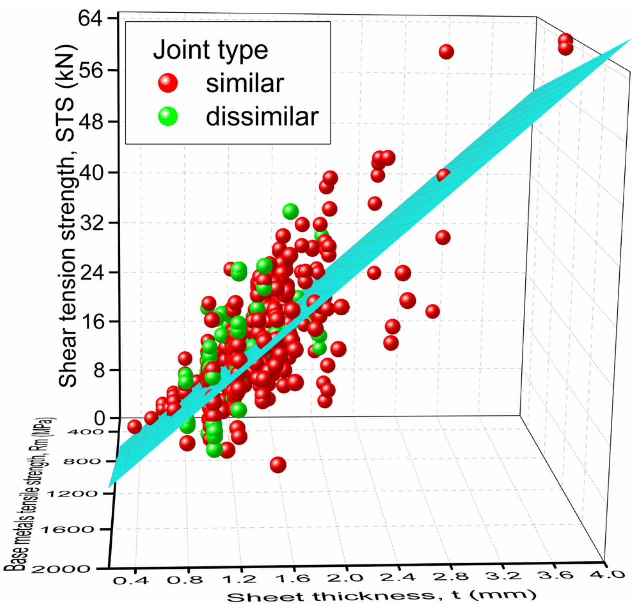

Fig. 11 Measured STS values are shown with the fitted plane according to Eq. (31), for similar and dissimilar RSWed joints. For the dissimilar joints, the weaker side is depictured.

compared to the previous fitting ($R^2 = 0.7$). It is still clearly seen, that, the main effect lies on the sheet thickness to be welded, and the base metals tensile strength also increases the STS values.

$$\mathrm{STS(kN)} = -9.58 + 15.32 \cdot t + 0.0087 \cdot R_m \quad (31)$$

Normalized STS values for Eq. (31) can be seen in Fig. 12. The scatter is small, normalized STS values are between ~0.5–2.0 and the values scatter symmetrically around 1. Therefore, with a safety factor >2 this correlation can be used in the whole R_m range to predict the STS values in the design stage of the given RSWed component.

3.2 Evaluation of the CTS correlations

From the listed equations for the CTS values (Eqs. (21)–(30)) some could already be used in the planning stage for normal loaded RSWed joints. Of course, interfacial fracture is to avoid here too. If, the concrete material is not yet known for the part to be welded only the required tensile strength and thickness, Eqs. (26), (28) and Eq. (30) can be applied, therefore the literature data for those correlations was tested. CTS data for optimized joints from ~100 papers were analyzed. The CTS values for the optimized joints is plotted in Fig. 13 [12, 21, 23, 25, 33, 38, 39, 42, 43, 49, 60, 66, 67, 71, 80, 83, 84, 86, 100, 107–109, 118, 134, 136, 143, 146, 150, 153, 158, 166, 167, 170–175, 179, 182–186, 188–190, 197, 200, 203, 206, 209–212, 214–220, 228, 232, 234, 235, 238, 249, 250, 266, 273, 275–304, 305]. The dissimilar joints were represented as weaker side of the joint according to the requirement (Eq. (30)) of the AWS D8.1M:2013 standard [28].

The measured CTS values vs. the sheet thickness are plotted on Fig. 14.

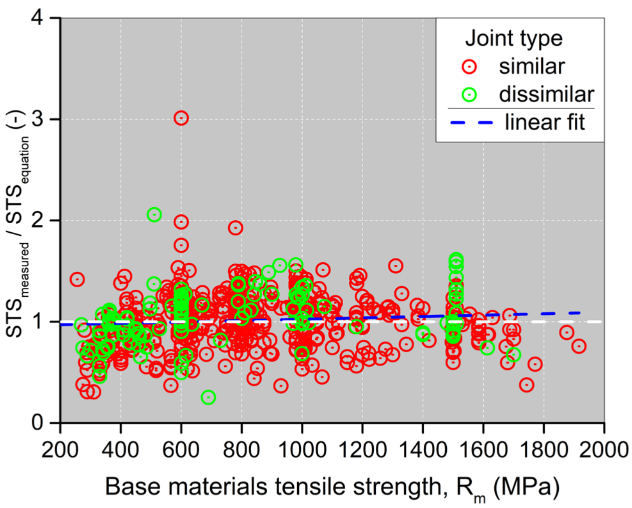

Fig. 12 Normalized STS values are shown according to Eq. (31), for similar and dissimilar RSWed joints. For the dissimilar joints, the weaker side is depictured.

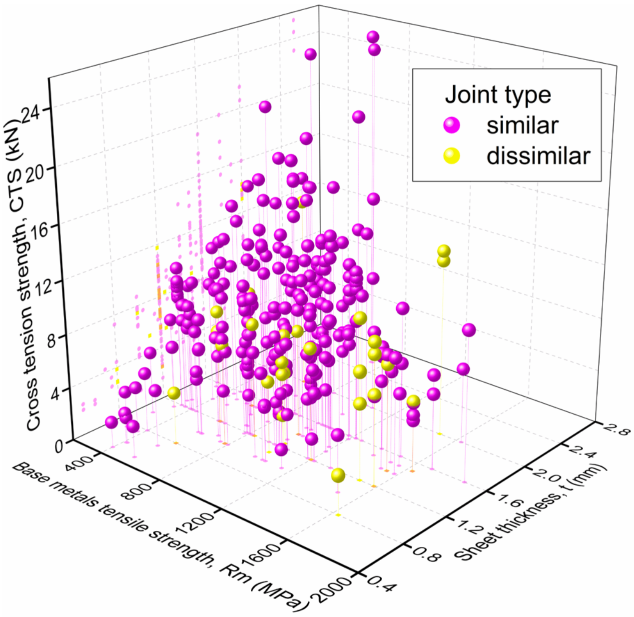

Fig. 13 Graphical representation of the literature data of the measured CTS values is shown in similar [12, 21, 23, 25, 33, 38, 39, 42, 43, 49, 60, 66, 67, 71, 80, 83, 84, 86, 100, 107–109, 134, 136, 143, 146, 150, 153, 158, 166, 167, 170–175, 179, 182–186, 188–190, 197, 200, 203, 206, 209–212, 214–220, 228, 232, 234, 235, 238, 249, 273, 275–304] and dissimilar [38, 43, 67, 107, 118, 134, 170, 214, 249, 250, 266, 282, 304, 305] RSWed joints.

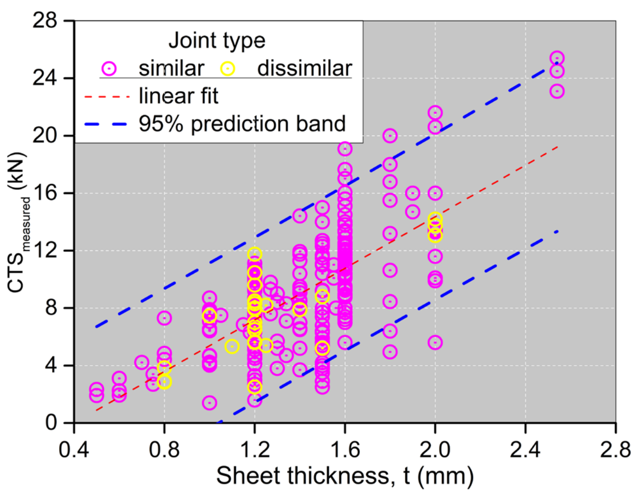

Fig. 14 The measured CTS values are shown for similar and dissimilar RSWed joints. For the dissimilar joints, the weaker side is depictured according to Eq. (30).

According to this diagram, the CTS values increase significantly with the sheet thickness, but the scatter is really high, e.g., for a steel sheet thickness of 1.6 mm the measured CTS values were between 6–18 kN. After linear fitting the CTS values for 1.6 mm thick sheets are predicted to be in the very wide range of 5–16 kN (95% prediction band). Therefore, the applicability of such equations where the sheet thickness is the only parameter for predicting the CTS values beforehand seems to be very limited.

In Fig. 15 the Eq. (30) (AWS D8.1M:2013 standard [28]) is investigated. As it can be seen, it fulfills its purpose by completely describing the minimal acceptable CTS values, because utmost normalized CTS values are above 1. (The same can be observed also in Fig. 16). The normalized values are basically in the whole investigated R_m range between 1–6 (eventually even 9) and a decreasing trend with higher R_m values can be observed. Therefore, Eq. (30) is not recommended for calculating the actual CTS value in the design stage.

As it was mentioned earlier, the nugget diameter d for good quality joints should be in the range of $3.5 - 5 \cdot \sqrt{t}$,

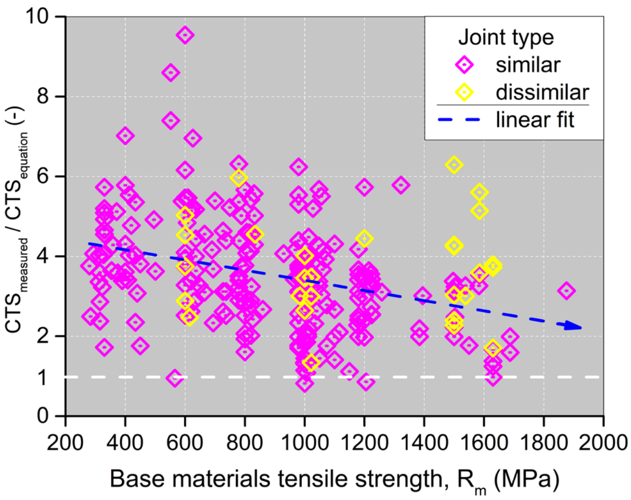

Fig. 15 Normalized CTS values are shown according to the requirement (Eq. (30)) of the AWS D8.1M:2013 standard [28] for similar and dissimilar RSWed joints. For the dissimilar joints, the weaker side is depictured.

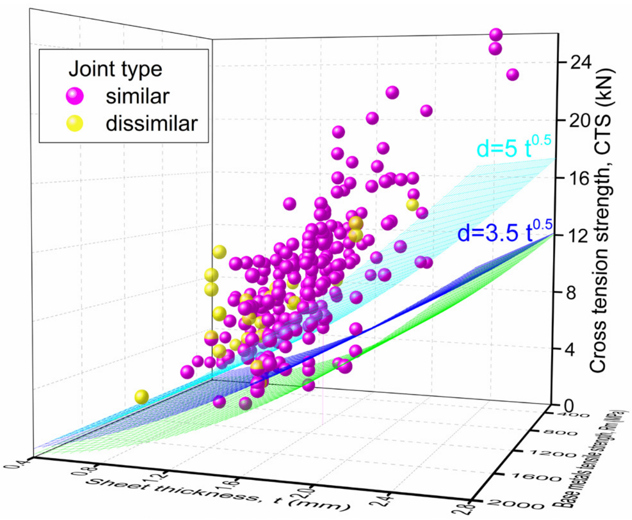

Fig. 16 Graphical representation of the literature data of the measured CTS values is shown in similar and dissimilar RSWed joints, planes are shown according to Eq. (26) (for different weld nugget sizes) in blue and according to Eq. (30) in green. The weaker side is depicted according to Eq. (30) for the dissimilar joints.

therefore Eq. (26) was investigated in this range. As it can be seen in Fig. 16, calculating with the nugget size $d = 3.5 \cdot \sqrt{t}$, Eq. (26) could be used as a boundary for the minimal acceptable CTS values similar to Eq. (30), but here a few more CTS values fall under the acceptance criteria. Increasing the assumed nugget size also increases the number of CTS values that fall under the acceptance criteria.

In the normalized CTS value plot for Eq. (26) for $d = 5 \cdot \sqrt{t}$ (Fig. 17) a slight decreasing trend for the normalized CTS values with higher base materials strength can be observed (~1.8±0.8 at R_m = 300 MPa decreased to ~1.2 at R_m = 1800 MPa). Still, the values scatter in a smaller range (between 0.5–3) than for Eq. (30) therefore with a safety factor >2 Eq. (26) could be used for predicting the CTS of the joint, for design purposes.

Equation (28) is beneficial, because it takes not only the sheet thickness and nugget size, but also the base materials tensile strength into account. Sakuma and Oikawa [23] and Sakuma et al. [24] determined for their investigation's coefficient J = 1.2–2.7. For the global approach in the whole tensile strength range the normalized CTS values are plotted for $d = 3.5 \cdot \sqrt{t}$ and $d = 5 \cdot \sqrt{t}$ in Fig. 18. As it is obvious the normalized CTS values are constantly decreasing, and at some R_m (depending on the nugget size and factor J) it falls below 1. However, this correlation works well for the selected steel group in [23, 24], it does not give a global approach to predict CTS values, for design purposes in the whole tensile strength range.

A plane fitting on all the literature data of similar joints was made (Fig. 19) with Origin® software to cover the whole steel sheet range.

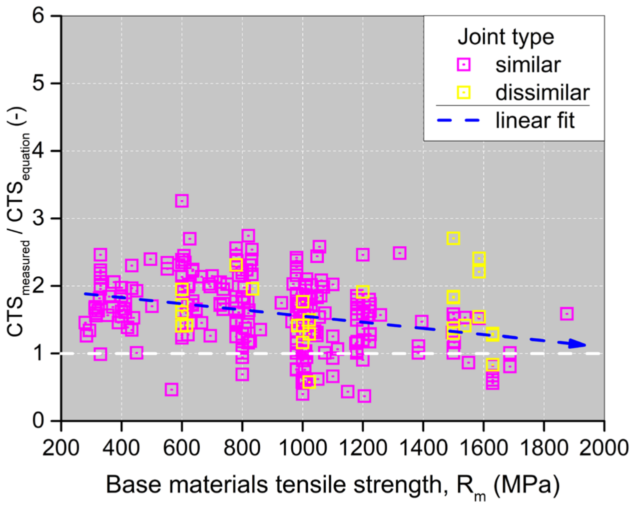

Fig. 17 Normalized CTS values are shown for Eq. (26) for similar and dissimilar RSWed joints, for the assumed nugget size $d = 5 \cdot \sqrt{t}$. For the dissimilar joints, the weaker side is depictured.

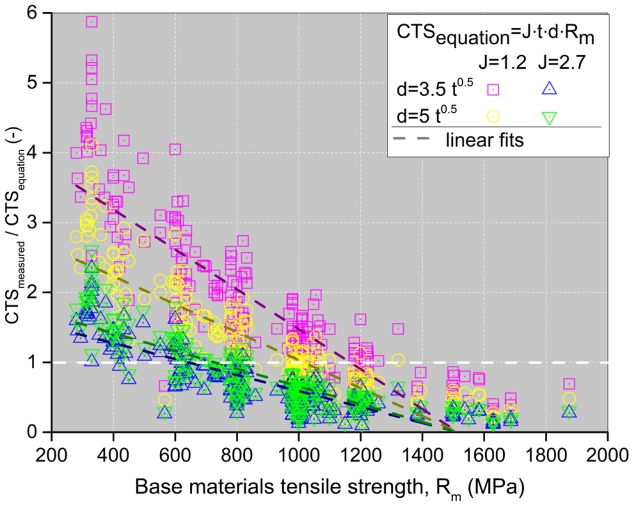

Fig. 18 Normalized CTS values are shown according to Eq. (28) (for J =1.2 and 2.7 the nugget sizes $d = 3.5 \cdot \sqrt{t}$ and $5 \cdot \sqrt{t}$) for similar RSWed joints.

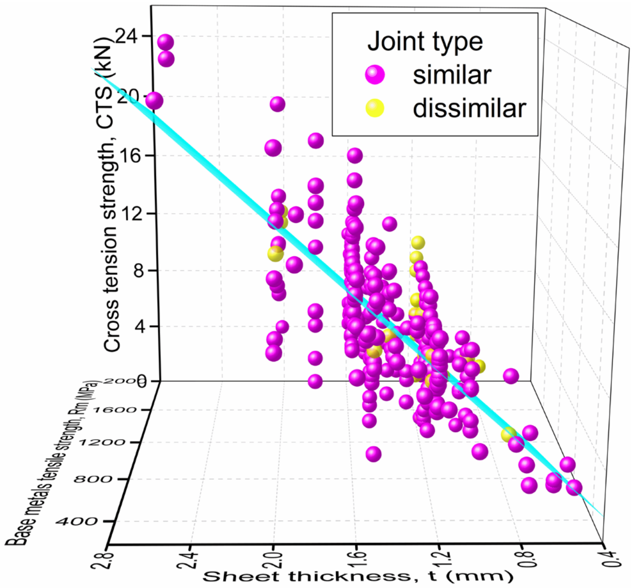

Fig. 19 Measured CTS values are shown with the fitted plane according to Eq. (32) for similar and dissimilar RSWed joints, for the dissimilar joints, the weaker side is depictured.

The fitted plane equation is Eq. (32).

$$\mathrm{STS(kN)} = -1.74 + 9.76 \cdot t - 0.0034 \cdot R_m \quad (32)$$

According to Eq. (32) in the investigated range it seems; that the main effect on the CTS has the sheet thickness which increases its value and the base materials tensile strength slightly but decreases the achievable CTS.

The normalized CTS values for Eq. (32) can be seen in Fig. 20. For similar joints the normalized values scatter around 1 and they are between 0.5–2. In the case of the dissimilar joints if there is a large difference in the sheet

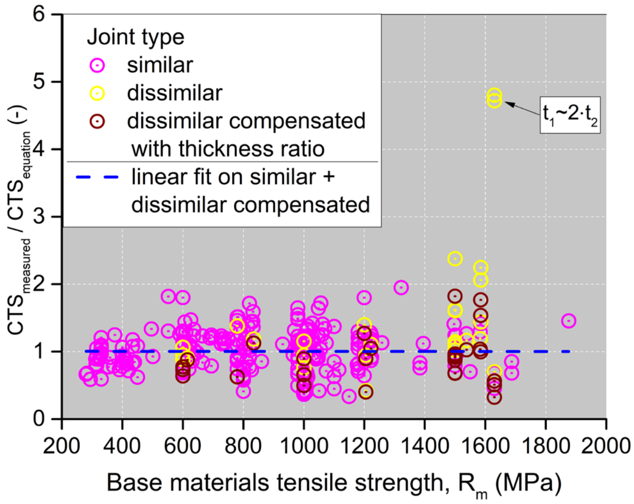

Fig. 20 Normalized CTS values are shown according to Eq. (32) for similar and dissimilar, and according to Eq. (33) for dissimilar (compensated) RSWed joints. For the dissimilar joints, the weaker side is depictured.

thickness of the two sides of the joint there were some high values ~5. Therefore, in the case of the dissimilar joints the CTS values were compensated proportional with the sheet thickness ratios according to Eq. (33).

$$\begin{aligned}\mathrm{STS(kN)} &= \left(-1.74 + 9.76 \cdot t_1 - 0.0034 \cdot R_{m1}\right) \cdot t_1 / \left(t_1 + t_2\right) \\ &+ \left(-1.74 + 9.76 \cdot t_2 - 0.0034 \cdot R_{m2}\right) \cdot t_2 / \left(t_1 + t_2\right)\end{aligned} \quad (33)$$

After this compensation, normalized CTS values for the dissimilar joints are in the region of 0.4–2 too. According to these results, for similar joints Eq. (32) and for dissimilar joints Eq. (33) can be used in the planning stage of RSWed parts in the whole tensile strength range for thin sheets. For application the usage of a safety factor 2> is needed.

4 Conclusions

In this study significant amount of literature data on resistance spot welding was analyzed and evaluated according to different kinds of shear tension strength and cross tension strength formulas. It was determined whether they are applicable to predict the strength of the RSWed joints in the planning stage of the manufacturing if only the sheet thickness and tensile strength of the base materials is known.

The literature data analysis using the different STS correlations showed:

- The AWS D8.1M:2013 standard's [28] equation (Eq. (17)) gives a good boundary for minimal achievable STS values in the whole tensile strength range, but to estimate the STS beforehand is not really applicable.
- Sawhill and Baker's [10] equation (Eq. (2)) with A = 2.2 and a presumed nugget size $d = 3.5 \cdot \sqrt{t}$ gives also a good boundary for minimal acceptable

STS values in the whole tensile strength range, but to estimate the STS beforehand is not really applicable either.
- Xu et al.'s [31, 32] equation (Eq. (20)), seems to be applicable to estimate the STS in the whole tensile strength range (with a safety factor ~3 needed).
- A new formula was proposed (Eq. (31)), which is even more applicable to estimate the STS depending on the steels sheet thickness (0.3–3.8 mm range) and their tensile strength (300–1900 MPa range), (with a safety factor ~2 needed).

The literature data analysis using the different CTS correlations showed:
- The AWS D8.1M:2013 standard's [28] equation (Eq. (30)) gives a good boundary for minimal achievable CTS values in the whole tensile strength range, but to estimate the CTS beforehand is not really applicable.
- Oikawa et al.'s [12, 13] equation (Eq. (26)) with a presumed nugget size $d = 3.5 \cdot \sqrt{t}$ gives also a good boundary for minimal acceptable CTS values in the whole tensile strength range and also seems to be applicable to estimate the CTS (with a safety factor >2 needed).
- A new formula was proposed to predict the cross tension strength for similar (Eq. (32)) and dissimilar (Eq. (33)) joints as well, depending on the steels sheet thickness (0.5–2.6 mm range) and their tensile strength (300–1900 MPa range), respectively (with a safety factor >2 needed).

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