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# Prediction of the Shear Tension Strength of Resistance Spot Welded Thin Steel Sheets from High- to Ultrahigh Strength Range

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**Abstract**

The tensile strength of newly developed ultra-high strength steel grades is now above 1800 MPa, and even new steel grades are currently in development. One typical welding process to join thin steels sheets is resistance spot welding (RSW). Some standardized and not standardized formulas predict the minimal shear tension strength (STS) of RSWed joints, but those formulas are less and less accurate with the higher base materials strength. Therefore, in our current research, we investigated a significant amount of STS data of the professional literature and our own experiments and recommended a new formula to predict the STS of RSWed high strength steel joints. The proposed correlation gives a better prediction than the other formulas, not only in the ultra-high strength steel range but also in the lower steel strength domain.

**Keywords**

resistance spot welding (RSW), advanced high strength steel (AHSS), ultra-high strength steel (UHSS), shear tension strength (STS)

## 1 Introduction

High strength steels (HSS) are gaining more and more attention and application in mechanical engineering, especially in the automotive industries [1–3]. Among high strength steels, advanced high strength (AHSS) and ultra-high strength (UHSS) steels are the most developing research areas due to their excellent mechanical strength (tensile strength $R_m$ > 1500 MPa) and adequate ductility, which are achieved during carefully selected thermo-mechanical heat treatment processes [4]. These mechanical properties make these types of structural steels lucrative for the application in automotive industries, e.g., crash boxes, car bodies, etc. [5]. Moreover, the increasing strength leads to the reduction in wall thicknesses. The smaller wall thicknesses have allowed engineers to manufacture lighter vehicles, which is very important in terms of fuel consumption, and, thus, in environmental considerations [6, 7].

The most important joining process of high strength thin sheets is welding. The arc welding of AHSS and UHSS can be challenging due to the unwanted phase transformations and the possible coatings [8–11]. For these reasons, the mostly applied joining process for AHSS and UHSS thin sheets is resistance spot welding (RSW) [12, 13]. RSW welding process can be easily automated [14, 15], robotized, therefore RSW is also an optimal process for mass production. RSW is also one of the most used welding process in car body manufacturing.

To improve weld quality and welding process efficiency new types of power sources with advanced electrical controls have recently been developed. They focus on the electronic control of the welding current and, thus, the heat input. Recently, extensive research hase been done in the field of the application of different pulsed welding technologies in the case of HSS welding. Kim et al. [15] investigated different pulse profiles to improve the weld quality of CP1180 steel. They have found that the volume of the weld nugget can be increased by pulse welding, and the weldable current range can be extended compared to single pulse welding. Pulse welding can also have beneficial effects in terms of metallurgical weldability. Wintjes et al. [16] have found that pulse welding schedules can reduce liquid metal embrittlement sensitivity in the case of zinc coated TRIP1100 steels. Liu et al. [17] have found that double pulse welding with higher secondary current can lead to an enhancement in shear tension strength in the case of

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Q&P 980 steel, due to the reduction of the partially melted zone. Multiple welding current pulses also act as a post weld heat treatment (PWHT). Stadler et al. [18] have found that the second welding current pulse remelted the center of the weld nugget of a 0.1 C, 6.4 Mn, 0.6 Si (wt%) medium Mn-steel, leading to a recrystallization and homogenization of the initial weld microstructure, thus improving the mechanical properties. For the optimization of welding process parameters design of experiments (DoE) methods have widely been used in RSW. Soomro et al. [19] have used Taguchi DoE to optimize PWHT parameters in order to obtain the maximum peak load and failure energy in RSW of DP590 steel. Tutar et al. [20] have used Taguchi method to optimize welding parameters for the RSW of TWIP sheets. They have found that the weld current has the highest statistical effect on the tensile-shear load, followed by the welding time and the electrode force. Artificial neural network is also a useful tool in terms of optimization. Rao et al. [21] have used neural network algorithm to obtain the optimized welding parameters. With the evaluation of shear tension strength, coach-peel strength and weld nugget size, the proper parameters were selected for the RSW of DP590 steel. Beside of the these highly developing welding technologies, design and evaluation methods, the conventional weld parameter design is still based on the shear tension strength and the failure mode of the RSW joint.

The shear tension strength (STS) values found in the literature is presented on Fig. 1 (according the data of [12, 17, 22–166]) for similar and dissimilar joints.

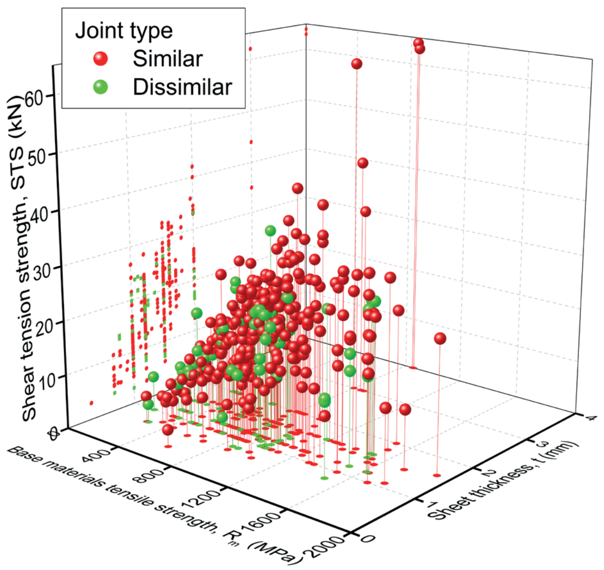


**Fig. 1** STS values of RSWed high- to ultra-high strength steels in similar [18, 23–142] and dissimilar [12, 23, 25, 36, 38, 43, 50, 78, 79, 82, 87, 96, 98, 100, 101, 115, 119, 125, 143–166] joint configurations

To the designer to plan joint configurations some formula is needed to predict the joint strength of RSWed high strength steels. Therefore, we made our research to refine such a correlation to predict the STS value.

Our current research is a follow up paper of a previously published work "About the shear tension strength of ultra high strength steels" [22]. Here a new correlation has been proposed to predict the STS values with better accuracy in the UHSS steel range ($R_m$ > 1340 MPa) for thin sheets (≤ 3 mm thickness). Now with more experimental and more literature data an even better correlation is proposed which is applicable for the whole high strength range for steels.

## 2 Equations to predict the shear tension strength

### 2.1 Different STS prediction models of the literature

There are different classifications for normal strength steels, HSS and UHSS in different literature, for our investigations we set the boundaries according to the American AWS D8.1M standard [167] to normal strength steel $R_m$ < 400 MPa, HSS 400 MPa < $R_m$ < 800 MPa and UHSS $R_m$ > 800 MPa, respectively.

There are several equations to predict the STS values for resistance spot welded steel sheets. One approach is according to the mentioned AWS D8.1M standard [167], which gives a guide for the minimum acceptable shear tension strength values ($STS_{AWS}$) in Eq. (1) for automotive applications.

$$STS_{AWS} = \frac{6.36\left(-6.36\cdot 10^{-7}\cdot R_m^2 + 6.58\cdot 10^{-4}\cdot R_m + 1.74\right)\cdot R_m \cdot 4 \cdot t^{1.5}}{1000}(kN) \quad (1)$$

In this formula $R_m$ is the tensile strength of the steel in MPa, and t the sheet thickness in mm. Due to the nature of this correlation (it has maxima at $R_m$ = 1340 MPa), the required $STS_{AWS}$ values start to decrease in the ultra-high strength steel range. It can be explained with the conservative nature of the standard, at some places of the joints even cracks are allowed. Presumably, the welding of such high-strength steel grades is challenging, and joint flaws are inevitable. Several research showed that UHSSs can be welded without defects free [28, 35, 44, 47, 72, 86–88, 98, 101, 166].

Nevertheless, this equation is not suitable for the design of RSWed steel structures with $R_m$ > 1340 MPa. To achieve the same structural strength, more spot welds are required than in case of lower strength base material. For example, for the welding of a $R_m$ = 1500 MPa steel the same STS is required for the joint as for a $R_m$ = 1200 MPa steel grade (see also in Figs. 2 and 3).

Investigating the professional literature and previous experiments of the authors about RSW of UHSS steels, it seems that the STS does not decrease in the $R_m$ > 1340 MPa range (Fig. 1). Therefore in our previous work [22], we modified the formula of AWS D8.1:2003 standard (Eq. (1)), to increase the minimum required STS value above the range $R_m$ > 1340 MPa (Eq. (2)).

$$STS_{New1} = \frac{\left[3788.77 - \left(-6.37 \cdot 10^{-7} \cdot R_m^2 + 6.58 \cdot 10^{-4} \cdot R_m + 1.7\right)\right] \cdot R_m \cdot 4 \cdot t^{1.5}}{1000} (kN) \quad (2)$$

In this formula $R_m$ is the tensile strength of the steel in MPa, and $t$ the sheet thickness in mm. This correlation gives a better prediction of the STS values in the UHSS range $R_m$ > 1340 MPa. Nevertheless, there is a shortcoming of both equations namely the required STS to actual STS ratio is decreasing with increasing $R_m$ of the base material. This ratio can be interpreted as a kind of safety factor, but the change over the $R_m$ range is not beneficial for the joint design.

The authors have also investigated other standards and correlations. The ISO 14373:2015(en) [168] gives a minimal requirement for low carbon (C < 0.15%, Mn <0.6%) steels (uncoated and zink coated till 3 mm thicknes). Most of the UHSS steels have also a low carbon content; therefore, we investigated this correlation too (Eq. (3)).

$$STS_{ISO} = \frac{2.6 \cdot t \cdot d_w \cdot R_m}{1000} (kN) \quad (3)$$

In this formula $d_w$ is the weld nugget diameter in mm, $t$ the sheet thickness in mm, and $R_m$ is the tensile strength of the steel in MPa. For this correlation, a required weld nugget diameter is needed.

Similarly, Radakovic and Tumuluru [59] defined some formulas for interstitial free (IF), transformation induced plasticity (TRIP), and dual phase steels (DP). One correlation is for predicting STS for pullout (PO) and one for interfacial (IF) fracture. Generally, the preferred fracture mode of RSWed joints is PO therefore the correlation for PO fracture (Eq. (4)) has been considered.

$$STS_{R\&T} = \frac{k_{PO} \cdot R_m \cdot t \cdot d_w}{1000} (kN) \quad (4)$$

In this formula $k_{PO}$ is a constant with the value of ~2.2, $R_m$ is the tensile strength of the steel in MPa, $d_w$ is the weld nugget diameter in mm, and $t$ the sheet thickness in mm. This equation is similar to the $STS_{ISO}$ function; only $k_{PO}$ is lower than the constant (2.6) in Eq. (3).

In both equations (Eqs. (3) and (4)) weld nugget size is an important parameter. The minimal weld nugget diameter commonly considered at least $3.5 \cdot \sqrt{t}$ (under this value is a risk of lack of fusion defects) and the maximum nugget size $5 \cdot \sqrt{t}$ or $6 \cdot \sqrt{t}$ (above that size there is a great risk of splash) [168]. Therefore, these correlations have been investigated in the $d_w = 3.5 \ldots 5 \cdot \sqrt{t}$ range.

### 2.2 Comparison of the different STS prediction models

The graphical representation of the previous models (Eqs. (1)–(3)) in the thin sheet range is shown in Fig. 2. The decreasing trend of $STS_{AWS}$ in the UHSS range ($R_m$ > 1340 MPa) is apparent. Also, there is a significant difference in the STS values of the different models with increasing $R_m$ and sheet thickness.

For example, in Fig. 3 the minimal STS values are plotted for the commonly available 1 mm sheet thickness in correlation with the tensile strength.

The model of AWS D8.1:2003 standard [167] (Eq. (1)) and the model of Radakovic and Tumuluru [59] (Eq. (3)) $d_w = 3.5 \cdot \sqrt{t}$ give approximately the same STS values in the range of $R_m$ < 800 MPa. The other models predict significant higher STS values than (Eq. (1)). For instance, in the high strength steel range (400 MPa < $R_m$ < 800 MPa),

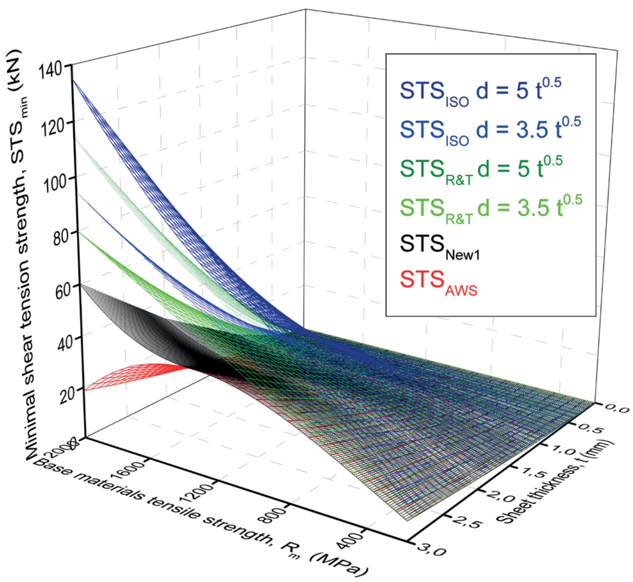


**Fig. 2** Graphical representation of the different STS prediction equations (Eqs. 1–4) in the thin sheet range

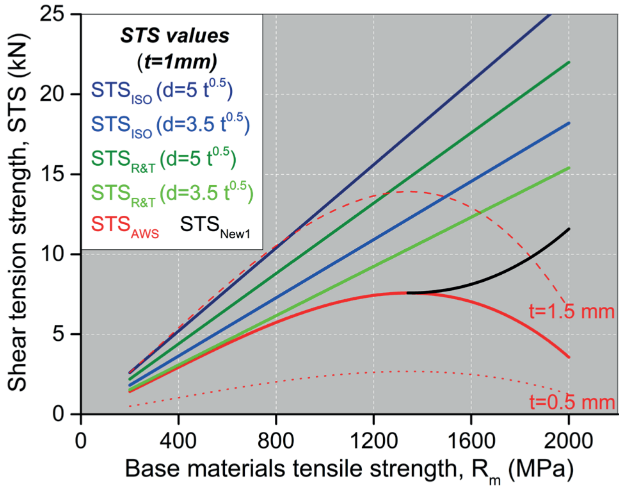


**Fig. 3** Graphical representation of the different STS models (Eqs. 1–4) for $t$ = 1 mm sheet thickness (except dotted lines for $t$ = 0.5 and 1.5 mm)

the predicted STS values according to the AWS standard for the sheet thickness of 1.5 mm are the same as the STS values according to the ISO standard with the nugget diameter $d_w = 5 \cdot \sqrt{t}$. The difference in the UHSS range ($R_m$ > 800 MPa) is even more severe. For example, for an UHSS with $t$ = 1 mm thickness and $R_m$ = 1600 MPa the $STS_{AWS}$ = 7.03 kN, $STS_{New1}$ = 8.12 kN, $STS_{R\&T}$ = 17.6 kN ($d_w = 5 \cdot \sqrt{t}$) and $STS_{ISO}$ = 20.08 kN ($d_w = 5 \cdot \sqrt{t}$), the difference between the lowest and highest estimation is about 300 %! This difference can be even higher at higher $R_m$ and sheet thicknesses.

Therefore, RSW experiments were performed and evaluated together with the literature data to better correlate the STS values.

## 3 RSW experiments

To complement the STS data from the literature, weld optimizations were made in the HSS and UHSS range in similar and dissimilar combinations. With the exception of the TRIP steel, which was produced as a test production by ISD Dunaferr Ltd, the other grades were produced by the company SSAB. The main properties of the base materials are listed in Table 1. The different steel types were designated according to their minimal guaranteed tensile strength ($R_m$ = 800–1700 MPa). The trade names of the DP 800 and DP 1000 sheets of steel are Docol 800DP, Docol 1000DP, for the CP 1000 steel Docol 1000CP and for the martensitic grades 1400 M, 1500 M, 1700 M are Docol 1400M, Docol 1500M, and Docol 1700M, respectively. The martensitic and bainitic wear-resistant steel grade has been designated according to its trade name as Hardox 450, where 450 is Brinell hardness of the steels.

**Table 1** Main properties of the base materials used for own RSW experiments

| Steel grade | Sheet thickness (mm) | CEV | $R_{p0.2}$ min. (MPa) | $R_m$ min. (MPa) | $A_{80}$ (%) | Hardness (HV10) |
|---|---|---|---|---|---|---|
| TRIP 800 | 1.2 | 0.21 | n.a. | 896 | 22 | 277 |
| DP 800 | 1.2 | 0.39 | 620 | 800 | 14 | 241 |
| CP 1000 | 1.4 | 0.41 | 800 | 1000 | 6 | 300 |
| DP 1000 | 1 | 0.39 | 700 | 1000 | 10 | 305 |
| 1400 M | 1 | 0.39 | 1150 | 1400 | 3 | 447 |
| 1500 M | 1 | 0.37 | 1200 | 1500 | 3 | 470 |
| 1700 M | 1 | 0.21 | 1350 | 1700 | 3 | 600 |
| Hardox450 | 1 | 0.46 | 1300 | 1820 | 4 | 475 |

The RSW experiments were made with a P.E.I.-POINT PN25 machine at 50 Hz frequency (AC), with P.E.I.-POINT PX 1500P control unit. The RSW welding unit had an X-type welding arm assembly, with $D$ = 5 mm diameter round CuCrZr electrodes. Electrode force was 1.9 kN. Welds were made with a simple work schedule. The varied parameters were the welding time and welding current. Both parameters can be set from 0 to 99 as integer values. Calibration curves were measured for the welding parameters by a BF Entron WA1 Weld Analyse type current measurement unit with a Rogowski coil. According to the calibration the welding time, welding current and welding voltage can be calculated by the Eqs. (5), (6) and (7), respectively.

$$\text{Welding time} = \text{welding cycles} \cdot 50/100(s) \tag{5}$$

$$\text{Welding current} = 1.73 + 0.12 \cdot \text{currrent setting of the RSW machine}(\text{kA}) \tag{6}$$

$$\text{Welding voltage} = 0.59 + 30 \cdot \text{currrent setting of the RSW machine}(\text{V}) \tag{7}$$

The RSW joints were optimized to achieve the highest STS value. The experiments were arranged with a central composite design (with Box-Wilson optimization) method [169].

The tensile-shear tests were performed with an MTS 810 universal material testing machine according to AWS D8.1M standard [167].

## 4 Results and discussion

### 4.1 Experimental STS data

The objective of the RSW experiments was to achieve the highest STS value with an acceptable weld quality. The STS values of the optimized joints and their welding parameters are listed in Table 2. It is evident from

**Table 2** Main properties of the base materials used for own RSW experiments

| RSW joint Sheet 1 | Sheet 2 | Sheet thickness (mm) | Current (-)/(kA) | Time (cycles) | STS (kN) |
|---|---|---|---|---|---|
| DP 800 | DP 800 | 1.2 | 60/8.9 | 30 | 23.0 ± 2.0 |
| TRIP 800 | TRIP 800 | 1.2 | 70/10.1 | 50 | 16.3 ± 1.9 |
| **TRIP 800 | TRIP 800 | 1.2 | 50/7.7 | 35 | 11.8 ± 0.9 |
| DP 800 | TRIP 800 | 1.2 | 45/7.1 | 45 | 17.3 ± 0.7 |
| CP 1000 | CP 1000 | 1.4 | 47/7.4 | 32 | 20.3 ± 1.2 |
| DP 1000 | DP 1000 | 1 | 45/7.1 | 20 | 13.7 ± 0.8 |
| 1400 M | 1700 M | 1 | 42/6.8 | 28 | 16.0 ± 1.0 |
| 1400 M | Hardox450 | 1 | 42/6.8 | 23 | 15.7 ± 0.7 |
| *1500 M | 1500 M | 1 | 35/5.9 | 20 | 14.9 ± 0.9 |
| *1500 M | Hardox450 | 1 | 50/7.7 | 30 | 16.4 ± 1.7 |
| *1700 M | 1700 M | 1 | 46/7.3 | 14 | 17.7 ± 0.6 |
| *1700 M | S 1300 | 1 | 42/6.8 | 21 | 13.9 ± 0.8 |
| *Hardox450 | Hardox450 | 1 | 50/7.7 | 30 | 22.0 ± 2.2 |
| **Hardox450 | Hardox450 | 1 | 50/7.7 | 20 | 20.1 ± 4.4 |

* Previously published here [22]; ** Different optimization method [67]

the table that the higher strength steels need to be welded with a shorter work schedule and higher current values. Moreover, the possible STS values are increasing with the base materials thickness.

All joints were defect-free and had the favorable pullout type fracture during tensile-shear testing.

It must be emphasized that the optimization for the highest STS was made within the boundaries of the RSW machine used in the experimental tests. Higher STS values could be achieved by: (a) using flat tip electrodes (other machine arm assembly required), (b) higher electrode force, (c) MFDC machine, (d) complex work schedule. This means the measured STS values are little less than the than the maximal achievable values for a given steel sheet. Which is not a big problem, because little underestimation of the highest achievable STS means staying on the safe side for the joint design for shear loading.

### 4.2 Evaluation of the STS data according to the literature models

The experimental STS data and those obtained from the literature are investigated here. Altogether those STS values are examined based on the different STS prediction models. On Figs. 4 and 5, the actual measured STS values are divided by the corresponding values obtained from the various models. Note: for dissimilar welds the calculations were done for the weaker side (according to th investigated formula) of the joint.

Dividing the actual values by the ISO (Eq. (3)) and the Radakovic and Tumuluru equations (Eq. (4)), a clear decreasing trend can be observed (Fig. 4(a) and (b), respectively) for similar and dissimilar welds in the whole tensile strength region.

The ratio of the measured and predicted STS values can be handled as a kind of safety factor (if greater than 1); therefore, it would be better if the ratio of the measured and predicted values would not change with the base materials $R_m$ range.

In Fig. 4(a), this ratio for $d_w = 3.5 \cdot \sqrt{t}$ is decreasing from ~ 2.5 till 1 at $R_m$ = 1600 MPa, at higher $R_m$ this model overestimates the actual STS of the welds. For a larger weld nugget this ratio decreases from ~2 to 1 till $R_m$ = 1200 MPa.

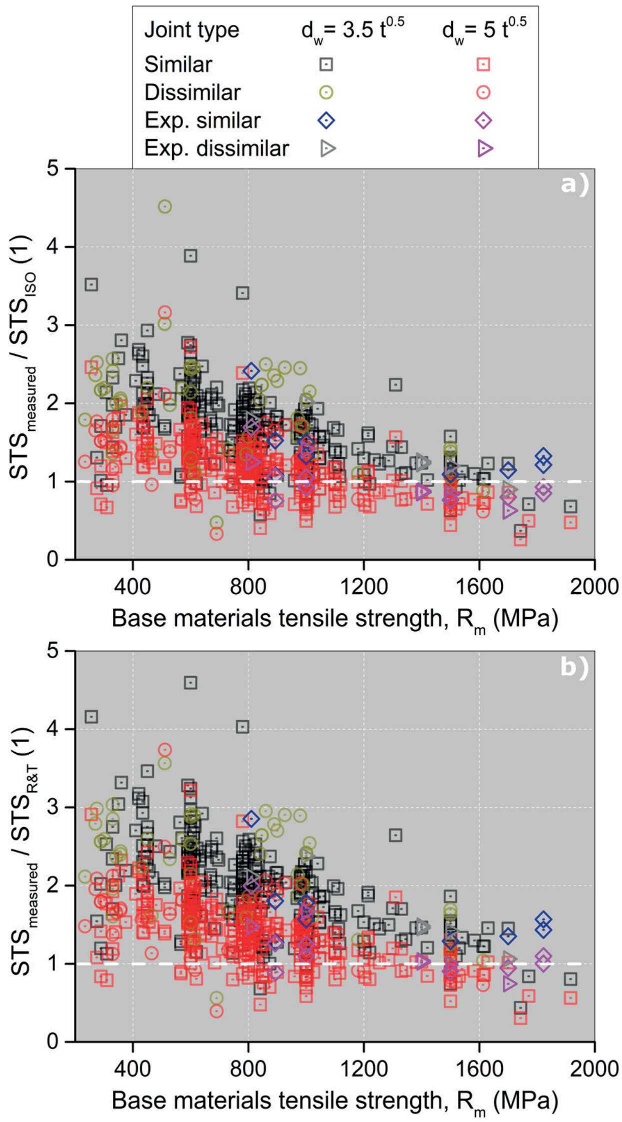


**Fig. 4** Measured STS values from the literature and the experimental (Exp.) data divided by the different STS functions (Eqs. (3) and (4)) for two different weld nugget sizes ($d_w = 3.5 \cdot \sqrt{t}$ and $d_w = 5 \cdot \sqrt{t}$)

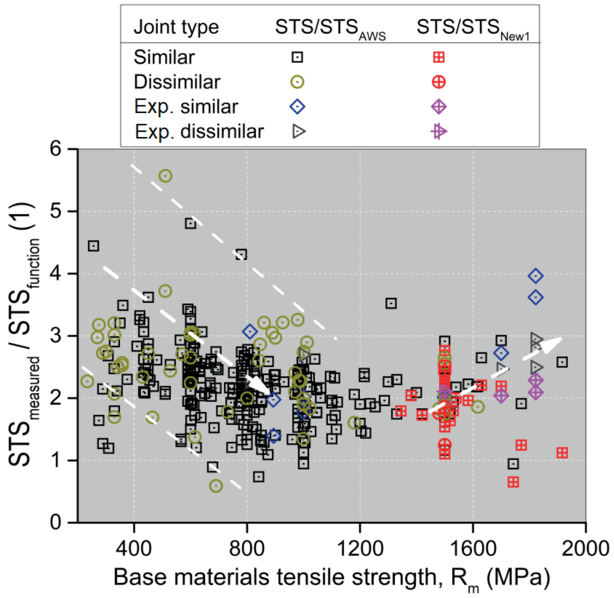


**Fig. 5** Measured STS values from the literature and the experimental (Exp.) work divided by the different STS functions (Eqs. (1) and (2))

In Fig. 4(b), the measured values being divided by the Radakovic and Tumuluru equation, which has the same characteristic as the ISO equation, showing very similar plots, only the transition of this quotient from > 1 to < 1 occurs at different base materials $R_m$. This ratio for $d_w = 3.5 \cdot \sqrt{t}$ begins with ~3 to decrease till 1 at base materials $R_m = 1600$ MPa, for $d_w = 5 \cdot \sqrt{t}$ from ~ 2 to 1 at $R_m = 1400$ MPa.

In Fig. 5, the values are divided by the AWS function (Eq. (1)) and at base materials $R_m > 1340$ MPa by the previous correlation proposed by the authors (Eq. (2)). This plot can be divided into two characteristic parts. Until $R_m \sim 1200$ MPa, the $STS_{measured} / STS_{AWS}$ values continuously decrease from ~ 4 to ~ 2, this ratio increases at higher base materials $R_m$ (on Fig. 5 indicated by white arrow at $R_m > 1340$ MPa). This means the measured values are lot higher than the predicted ones. It is not very beneficial for the designers, because designing according the $STS_{AWS}$ function means that they have to plan with more weld nuggets than necessary. For thath reason was Eq. (2) proposed previously [22]. In Fig. 5 it is evident that the increasing part of the ratio ceased with the application of Eq. (2) and stabilized around the ratio of 1–3.

### 4.3 Determination of a new STS prediction model

To have a more constant $STS_{measured} / STS_{predicted}$ ratio a new function has been determined based on experimental data and the STS data of about 150 papers [12, 17, 22–165]. All the STS data is represented in Fig. 6 as a 3D plot.

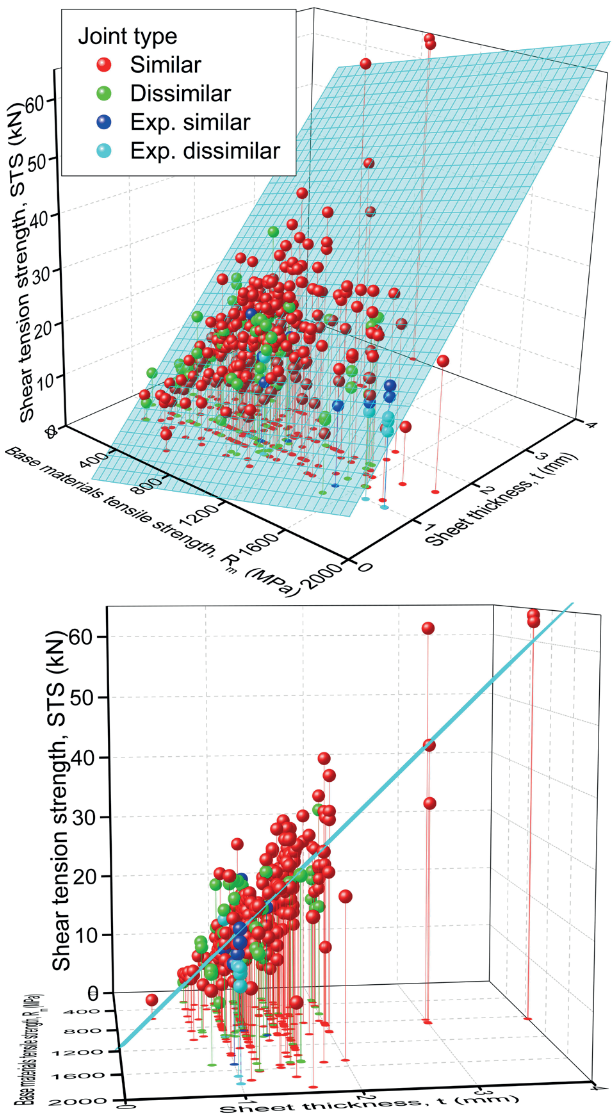


**Fig. 6** Measured STS values from the literature and experimental (Exp.) work and a fitted plane (Eq. (8))

Several types of linear and nonlinear surfaces have been fitted on the STS values. There is no significant difference between them for the current available information; therefore also for easier handling, a 3D plane function has been determined ($STS_{New2}$) (Eq. (8)).

$$STS_{New2} = -10.10 + 0.0088 \cdot R_m + 15.80 \cdot t \, (kN) \tag{8}$$

In this formual $R_m$ is the tensile strength of the steel in MPa and $t$ the sheet thickness in mm.

For comparison the different STS models are plotted for 1 mm sheet thickness in Fig. 7. In this case, the $STS_{New2}$ function predicts a higher STS value than the other equations, while at $R_m \sim 1345$ MPa it predicts lower strength than the $STS_{ISO}$ function for $d_w = 5 \cdot \sqrt{t}$. For larger sheet thicknesses, this transition shifts for the smaller base materials

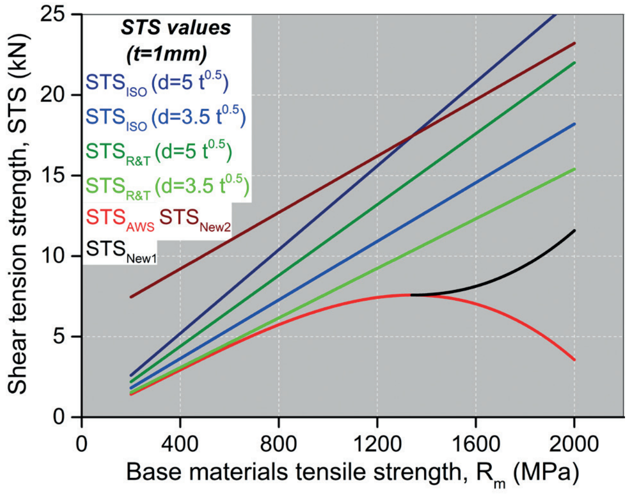


**Fig. 7** Graphical representation of the different STS models (Eqs. (1)–(4) and 8) for $t = 1$ mm sheet thickness

strength, e.g., for 2 mm sheet thickness the transition occurs at $R_m$ ~ 750 MPa, while at $R_m$ ~ 1600 MPa the predicted $STS_{New2}$ value is smaller than the $STS_{R\&T}$ value for $d_w = 5 \cdot \sqrt{t}$. So it seems Eq. (8) approximates better the measured STS values for the whole high strength base materials 400 MPa < $R_m$ ~ < 2000 MPa range for thin sheets.

### 4.4 Evaluation of the STS data according to the different models for selected HSS and UHSS types

The different STS prediction models were investigated especially for HSS ans UHSS steel grades. The most literature data was available for the DP, TRIP and martensitic steel grades in this strength regions. The measured STS values of these three grades (in similar joints) are divided by the different STS prediction functions are shown in Fig. 8.

*DP steel grades* are in the 400 MPa < $R_m$ < 1300 MPa range (Fig. 8(a)). The $STS_{measured} / STS_{function}$ values for the AWS model continuously decrease from approx. 2.5–3.5 range to 1–1.5 range with the higher $R_m$. In case of the ISO function (for $d_w = 5 \cdot \sqrt{t}$) this decreasing trend can still be observed, but at a smaller extent from approx. 2–1.5 range to 0.5–1.5 range. The values computed with the New 2 function (Eq. (8)) scatter in the whole $R_m$ range, homogeneously in the 0.5–1.5 range.

*TRIP steel grades* are in the 500 MPa < $R_m$ < 1300 MPa range (Fig. 8(b)). The $STS_{measured} / STS_{function}$ values for the AWS model are approx. 15–2.5 in the whole tensile strength range. In case of the ISO function (for $d_w = 5 \cdot \sqrt{t}$) this range is significantly narrower approx. 0.5–1.5. In the New 2 function (Eq. (8)), this range is slightly smaller approx. 0.4–1.4, and even smaller for $R_m$ < 700 MPa.

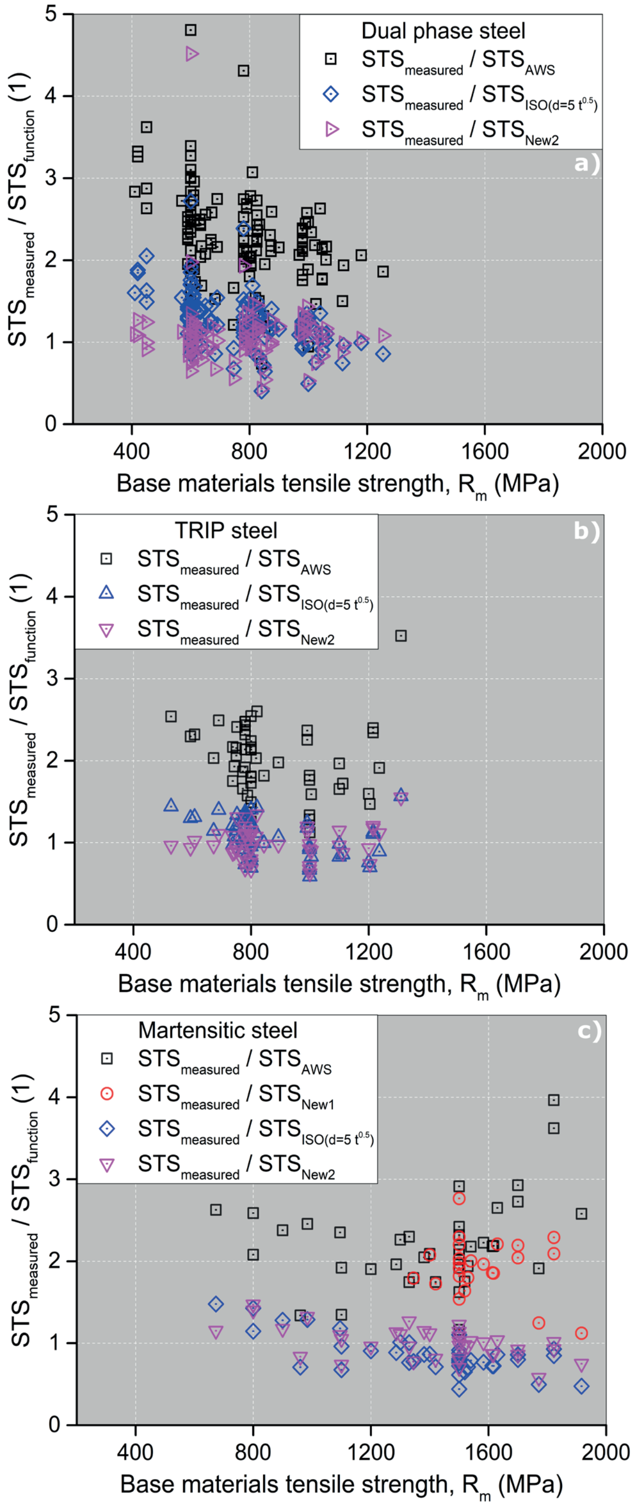


**Fig. 8** Measured STS values from the literature and experimental work divided with the different STS functions (Eqs. (1)–(3) and Eq. (8)) in similar joints for: DP steels a), TRIP steels b) and martensitic steels c)

*Martensitic steel grades* are in the 700 MPa < $R_m$ < 1900 MPa range (Fig. 8(c)). The $STS_{measured} / STS_{function}$ values for the AWS model are continuously decreasing from approx. 2.1–2.8 range to 1.8–2.5 range at the higher $R_m$.

Above $R_m$ = 1340 MPa, this ratio starts to increase again till ~ 2.6–3 range. These values for the New1 function (Eq. (2)) do not increase but are in the approx. 1.3–2.5 range. In the case of the ISO function (for $d_w = 5 \cdot \sqrt{t}$), this range is significantly narrower but the $STS_{measured} / STS_{function}$ values are continuously decreasing from the approx. 1–1.5 range to the 0.5–0.9 range at higher $R_m$. This means that this formula first underestimates the real STS values, than from approx. $R_m$ > 1200 MPa it overestimates them.

In case of the New 2 function (Eq. (8)), $STS_{measured} / STS_{function}$ range is smaller approx. 0.4–0.6 and the values are more homogeneously distributed in the whole $R_m$ range.

In Fig. 9 the measured STS values from the literature and from the experimental work are divided by the developed $STS_{New2}$ function (Eq. (8)) for similar and dissimilar joints. As it can be seen, the values scatter around 1, a fitted line with fixed intercept at 1 had a minimal slope of $3 \times 10^{-5}$ $MPa^{-1}$, with the $R^2$ of 0.9.

Therefore it can be concluded, that the new function approximates better the measured STS values in the whole $R_m$ range for similar and dissimilar joints than the existing literature and standards equations. Moreover, the equation has the advantage to be only dependent on the base materials tensile strength and the sheet thickness, and not on the weld nugget size.

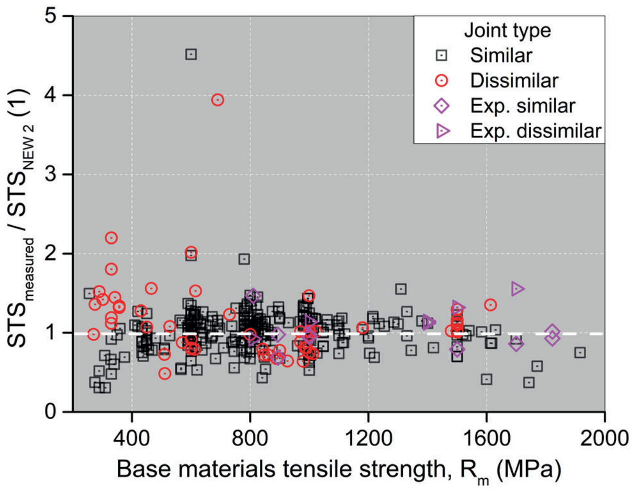


**Fig. 9** Measured STS values from the literature and experimental (Exp.) work divided by the developed new function (Eq. (8)) for similar and dissimilar joints

## 5 Conclusions

In this current research, a large amount of literature and experimental data have been investigated to better predict the shear tension strength (STS) of resistance spot welded high and ultra-high strength thin steel sheets. From the available data, the following conclusions can be drawn:

- The standardized AWS D8.1M function underestimates the measured STS values, and the ratio of $STS_{measured} / STS_{AWS}$ decreases with the material tensile strength, and due to the nature of this function it starts do increase again above 1340 MPa.
- The standardized ISO 14373:2015(en) [168] and the Radakovic D. and Tumuluru M. functions underestimate the measured STS values at lower base materials tensile strength, and the ratio of $STS_{measured} / STS_{function}$ decreases with the material tensile strength. At certain tensile strength (depending on the function and the required weld nugget size), this ratio is below 1 meaning that the functions start to overestimate the STS values.
- A new formula has been proposed (Eq. (8)), which gives a homogeneous $STS_{measured} / STS_{function}$ ratio (0.5–1.5 range) over the 400–1900 MPa base material tensile strength range. It also gives a narrower range of $STS_{measured} / STS_{function}$ values at any selected base materials strength. It also works better for DP, TRIP and martensitic steels. This formula is dependent on the base materials tensile strength and the sheet thickness, and not on the weld nugget size.
- The proposed new function can be a loocrative tool for the designers in the planning stage of resistance spot welded components made of thin sheets (approx. < 3 mm) under tensile-shear load.

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