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Strength of the Weld with Respect to Its Geometry

Abstract: The research presented in the article involved the analysis of the shape of a weld made using the spot resistance double-sided overlap welding of sheets. The analysis was performed using the 3D model of the weld. The analysis of between ten and twenty weld variants enabled the determination of the structure of the ideal weld. The ideal weld structure is composed of three parts, where a thin intermediate element (connector) is placed between two joined sheets. The entire model constitutes a mechanically inseparable whole, where both sheets and the intermediate element are made of the same material. The ideal weld is not subjected to a thermal cycle. The above-named model was supplemented with numerical calculations aimed to identify the most favourable shape of the weld (nugget), e.g. circular, rectangular etc. The criterion of assessment was the (highest possible) value of shear force obtained in a static tensile test [1]. The article presents the results of the initial stage of research on the ideal weld.

Keywords: spot resistance welding, weld geometry,

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Introduction

Publications, not only those related to resistance welding, are usually concerned with the modification of the technological process aimed to improve both the process and the quality of finished products. As regards resistance welding, authors usually define joint-related improvements through the obtainment of joints free from welding imperfections, increased process repeatability or higher strength of welded joints. However, authors' deliberations concerning the strength of joints usually lack the indication of its theoretical upper ultimate value.

Recommendations concerning spot resistance welded joints state that they be designed so that welds are subjected to shearing. It is necessary to avoid welds subjected to tension or torsion [p. 2 of 100]. For this reason, the major analytical criterion adopted in this article is the shear strength of the weld. Other strength-related criteria such as cross tensile strength, torsional strength or peel strength are not taken into consideration when assessing the quality of welds. In addition, the quality-related analysis does not include the depth to which electrode penetrate the material subjected to welding (so-called indent).

In the *ideal* weld, being the subject of this article, the analysis is concerned with the most favourable shape of the weld, i.e. the effect of the weld nugget shape on the strength of the welded joint. The thermal cycle, having a significant,

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yet unfavourable effect on structural changes not only in the weld material but also in the entire welding area (particularly in the heat affected zone) is not taken into consideration. The aforesaid approach, the lack of the effect of the thermal cycle, results in the lack of division into the base material, weld nugget and HAZ. For this reason, the analysis only involves the size and shape of the weld nugget surface in the plane perpendicular to electrodes, i.e. the plane in which elements are welded. The analysis does not take into consideration the height and shape of the weld nugget in the direction of the electrode axis as, because of the previously adopted assumptions, i.e. the lack of the thermal cycle, the numerical model does not include such an area.

The article presents results being a fragment of greater research focused on the proper quality of the weld. The subject of the research is the ideal weld, where the shape and the size of the weld nugget were also affected by force, its value and course. Electrode force or travel can be controlled using an electromechanical system. The tests performed and discussed in this publications involved the use of the classical, i.e. the pneumatic system of electrode force.

Analysis of Reference Publications

The analysis of reference publications involves the use of the term of the ideal weld, yet it primarily refers to the welded joint made ideally in physical terms. Article [3] analysed the appearance of the weld, whereas the analysis was a visual assessment in its nature. The analysis involved the comparison and the assessment of welded joints in relation to the depth of the indent left by the electrode in the material, the indent diameter, cracks and expulsion. Measurements were performed using a camera in a manner enabling the obtainment of quantitative results.

In article [4] the term of the ideal weld also refers to the weld made ideally in physical terms. The ideal weld is perceived as the joint free from various possible welding imperfections. The authors mention the presence of numerous hard-to-identify obstacles and factors which affect the obtainment of the ideal welded joint.

In available reference publications, the notion of the ideal weld was attributed to welded joints obtained in technological welding tests, i.e. where, as a result of the flow of current, the material being welded was subjected to the thermal cycle. However, the publications did not contain information concerning the ideal weld as presented in this article, i.e. the analysis of the weld in terms of shear strength with the deliberate ignoring of the thermal cycle.

Assumptions Adopted When Calculating the Ideal Weld

The analysis involved between ten and twenty variants of the ideal weld. The calculations and experiments involved 1.5 mm thick sheets in steel grade DX53. The analysis was focused on various:

– weld nugget shapes, i.e. circular, square and rectangular,
– weld area,
– double systems of the welds (serial, parallel) in relation to the direction of shear force.

The calculations were performed using the SORPAS software [5]. In the computational model the ideal joint of the sheets involved the use of an additional element, a so-called connector. The non-zero value of the connector height resulted from the lacking possibility of the “gluing” of the elements of sheets in the computational model having assumed shapes and dimensions of the ideal weld nugget, e.g. the circular weld nugget. Exceptions were the variants of non-overlap joints (M9) and the variant designated as the “gluing” of sheets (M2), in relation to which the value of the connector amounted to zero.

The analysis involved various values restricted within the range of 0.01 to 1.0 mm (Fig. 1). To ensure the highest possible accuracy of calculations (FEM) and because of the fact that the connector adopted for the calculations does not exist in practice, the numerical calculations were performed adopting the lowest possible height of the connector amounting to 0.2 mm, i.e. the value recognised as sufficient for accurate numerical modelling (SORPAS) [5]. The adoption of higher values of the connector height did significantly not increase the strength of the weld, whereas the reduction of the connector height decreased the strength of the weld and, consequently, reduced the accuracy of calculation results (Fig. 1). In addition, the adopted connector height (0.2 mm) was not connected with the introduction of an artificial notch which could initiate cracks, particularly at the beginning of a shear test (which could result from sharp edges of the computational model geometry). The above-presented model (as indicated by related calculation results) enabled the accurate and complete analysis of phenomena occurring during shearing, e.g. elongation.

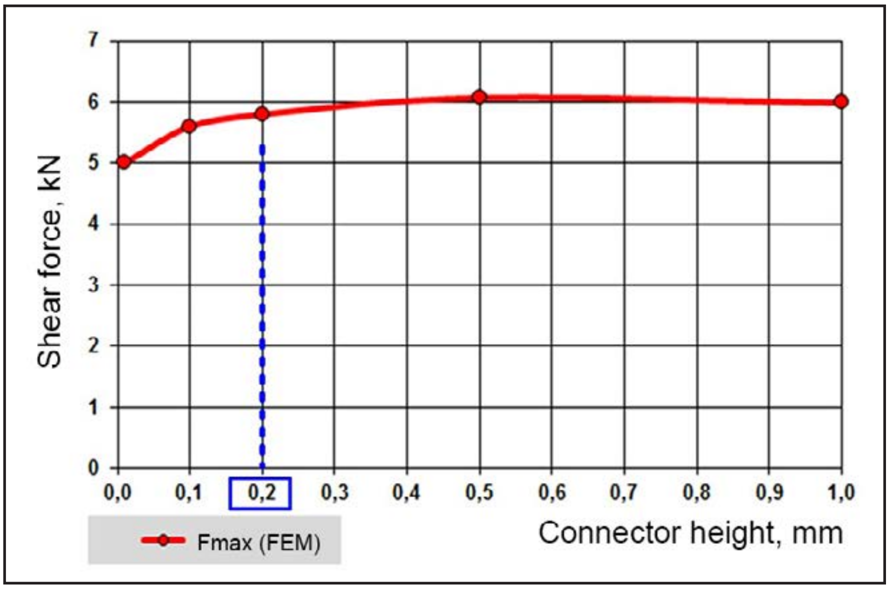

Fig. 1. Effect of the connector height on the value of shear force in a static tensile test (FEM calculations)

In nine variants subjected to analysis (from M1 to M9) the ideal weld (sheets and the intermediate element, i.e. the connector) constituted one mechanically inseparable element. The material of all of the ideal weld elements was the same, and the whole was not subjected to the thermal cycle. The entire joint had the properties of the base material (sheet), which means that the joint was not exposed to the unfavourable effect of the thermal cycle. In the FEM calculations it was necessary to use the minimum value of current (0.1 kA) and a very short time of current flow (1 ms) because of the specific operation of the SORPAS software programme requiring the setting of the minimum time and current to perform conjugated calculations including heating and a shear test [5]. However, such current parameters do not have a significant effect on changes in the temperature of the material, and, as a result, on the temperature-related (metallurgical) properties of the material. Other adopted model parameters were the following:

- sheet (specimen) width of 30 mm – in relation to a single joint (one weld) and 55 mm in relation to double joints in the parallel system of welds in relation to the direction of the shear force effect,
- sheet length of 70 mm - in relation to a single joint (one weld) and 95 mm in relation to double joints in the in the serial system in relation to the direction of the shear force effect.

The numerical calculations involving the first nine variants (M1 – M9) were performed to determine the shear strength in relation to the so-called ideal weld. Variants M10 and M11 present the strength of the weld in relation to the *computational* welding process, for the high and low welding parameters (Table 2) respectively. The shear test followed the welding process-related calculations (FEM), where welding parameters affected the diameter and height of the weld nugget as well as influenced the distribution of temperature in the welding area. The shear test constituted the second (conjugated with the first) stage of numerical calculations performed using the SORPAS software programme [5]. The parameters used in the calculations are presented in Table 1.

Table 1. Parameters of FEM calculations

	Initial force	Time of current flow	Final force	
Calculation step	1	1	1	ms
Recordong of data	5	5	5	steps
Welding paramaters				
Variant number	Current	Time	Force	Final force
	kA	ms	kN	ms
M1-M9	0.1	1	0.1	---
M10 (high parameters)	10	160	3.0	500
M11 (low parameters)	7	400	1.5	500
Convergence of calculations (covergence control)				
	level of convergence			
Electric model	1.00E-5			
Thermal model	1.00E-5			
Mechanical model	1.00E-5			
Heat losses to the environment				
Ambient (air) temperature	20		°C	
Heat transfer coefficient	300		[W/m2*K]	
Electrode type	F0			
Welding current type	DC 1 kHz			
Force system	pneumatic			

Table 2. Characteristic parameters of the ideal weld in relation to SORPAS numerical calculations [5]

No.	Variant number	Weld nugget shape	Weld nugget dimensions	Cross-sectional area of joint (weld)	Height of connector	Remarks
			mm	mm²	mm	
1	M1	circle	$\phi = 6.00$	28.26	0.2	reference variant
2	M2	square	$x = y = 5.316$	28.26	0.0	“gluing” of sheets
3	M3	square	$x = y = 5.316$	28.26	0.2	---
4	M4	rectangle	$x = 10.00$; $y = 2.826$	28.26	0.2	---
5	M5	rectangle	$x = 2.826$; $y = 10.00$	28.26	0.2	---
6	M6	2 circular weld nuggets	$2 \times \phi = 6.00$	2×28.26	0.2	2 circular weld nuggets, system of 2 serial welds, $l = 50$ mm
7	M7	2 circular weld nuggets	$2 \times \phi = 6.00$	2×28.26	0.2	2 circular weld nuggets, system of 2 parallel welds, $l = 50$ mm
8	M8	2 circular weld nuggets	$2 \times \phi = 4.24$	2×14.13 $\Sigma = 28.26$	0.2	2 circular weld nuggets, system of 2 parallel welds, $l = 25$ mm
9	M9	uniform sheet	$k = 18.84$ mm $g = 1.5$ mm (Fig. 8)	28.26	0.0	non-overlap joint (butt)
10	M10	circle	$\phi = 6.00$	28.26	0.2	high welding parameters [T], $i = 10$kA, $t_{zgrz} = 160$ms, $F = 3.0$kN [2]
11	M11	circle	$\phi = 6.00$	28.26	0.2	low welding parameters [M], $i = 7$kA, $t_{zgrz} = 410$ms, $F = 1.5$kN [2]

Analysed Joint Variants

Table 2 presents the analysed variants of (FEM) numerical calculations designated using the letter *M* (as in *Finite Element **M**ethod*) and a related number. Variants presented in Table 2 include the shape and dimensions of the weld nugget, including the height of the connector (h). To verify the FEM-based calculations the analysed variants were subjected to technological welding tests; the above-named variants are designated using the letter *E* (as in ***E**xperiment*).

The *x*-coordinate represents the weld nugget dimension in the parallel direction, whereas the *y*-coordinate represents the weld nugget dimension in the perpendicular direction in relation to the shear force effect.

Numerical Models of Analysed Variants

Figure 2-9 present the shapes of the weld nugget and the specimens in relation to the selected variants of the computational model along with the mesh and characteristic dimensions. Figure 9 presents the direction of shear force application in relation to elements being welded. The analysis involved the circular and rectangular shape of the weld nugget (connector). Figure 2 presents the schematic diagram of the analysed shapes of the connector along with its dimensions:

- circular weld nugget having nominal diameter $\phi_1 = 6.0$ mm (S_1=28.26 mm^2) in relation to 1.5 mm thick sheets (Fig. 2b),
- circular weld nugget having a twice smaller area S_2= 14.13mm^2 (1/2 × 28.26 mm^2), i.e. diameter ϕ_2=4.24 mm,
- square weld nugget (Fig. 2b) and rectangular weld nugget (Fig. 2a/c).

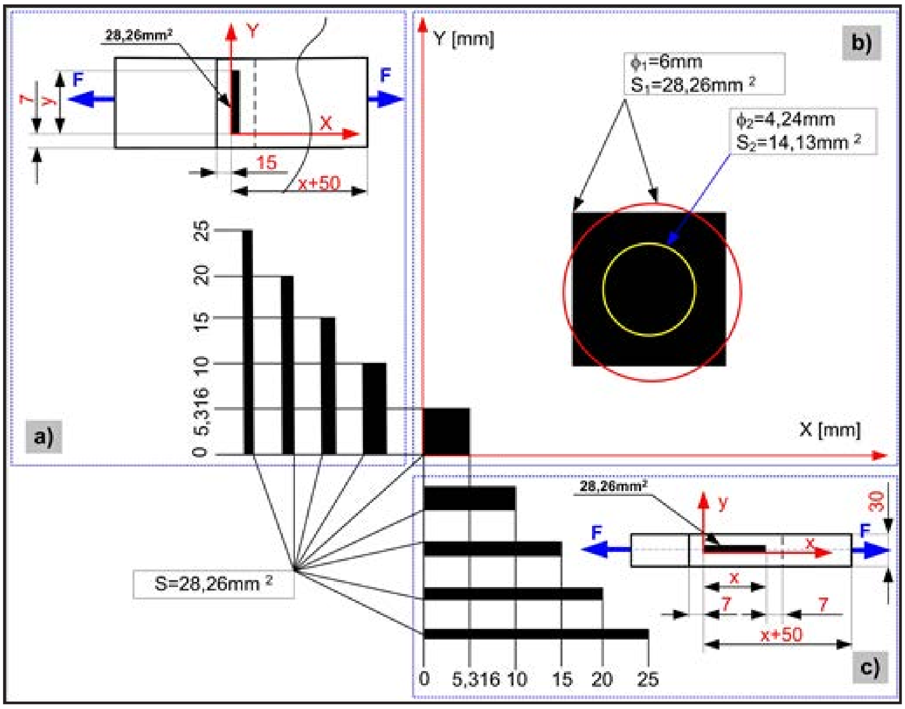

Fig. 2. Analysed shapes and dimensions of the weld nugget

Figures 3-8 present the geometric details of the numerical model (in particular the shape of the specimens), in relation to which the numerical calculations concerning the shear force were performed.

- figure 3 – variant M1, circular weld nugget, the diameter and the height of the connector $\phi = 6$ mm and $h = 0.2$ mm respectively,
- figure 4 – variant M2, square weld nugget $x = y = 5.316$ mm (“gluing” of sheets),
- figure 5 – variant M5, rectangular weld nugget, ($x = 10$ mm, $y = 2{,}826$mm),
- figure 6 – variant M6, two circular weld nuggets in the system of serial welds ($2 \times \phi_{nugget} = 6{,}0$ mm),
- figure 7 – variant M8, two circular weld nuggets in the system of parallel welds ($2 \times \phi_{nugget} = 4{,}24$ mm),
- figure 8 – variant M9, non-overlap (butt) joint, (S=28,26mm^2),

Figure 9 presents the model used in the numerical calculations concerning the welding process and the tension (shearing) of the specimen. The calculations aimed to obtain a welded joint characterised by specific parameters, i.e. the weld nugget diameter and to determine the shear strength in relation to the obtained joint (weld nugget size).

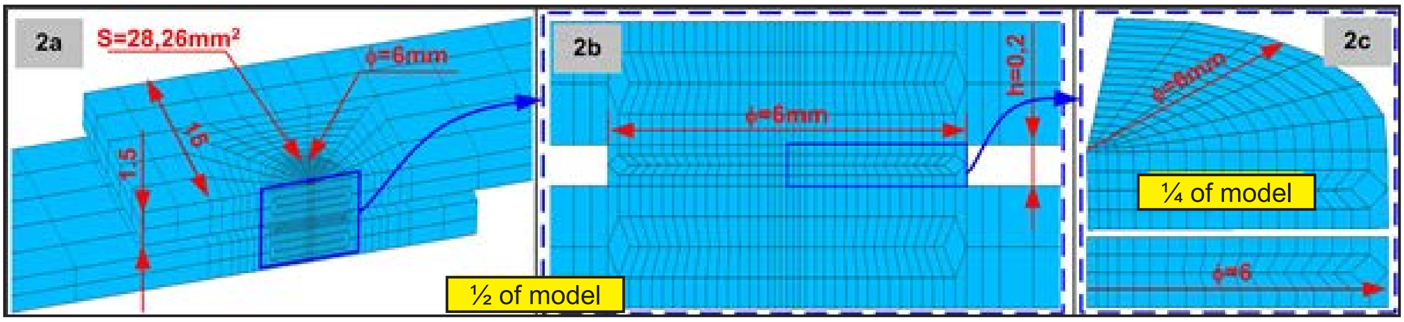

Fig. 3. Shape and dimensions of the specimen (variant M1)

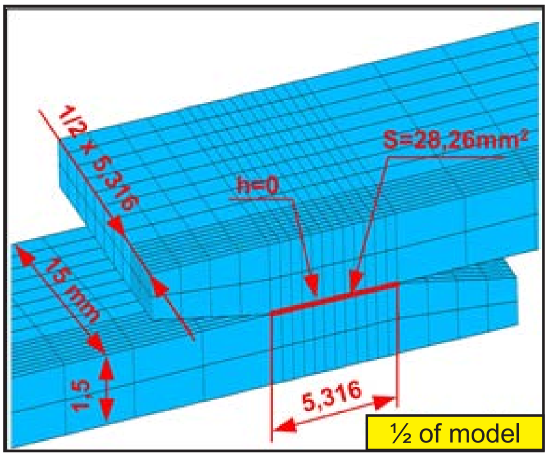

Fig. 4. Shape and dimensions of the specimen (variant M2)

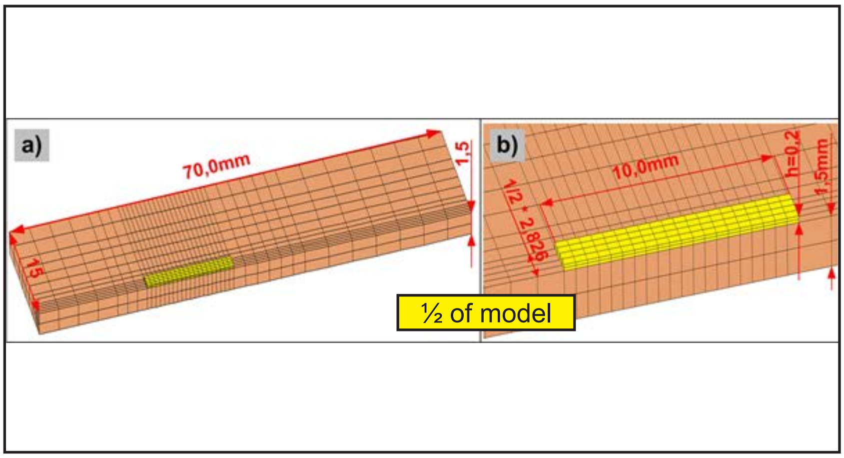

Fig. 5. Shape and dimensions of the specimen (variant M5)

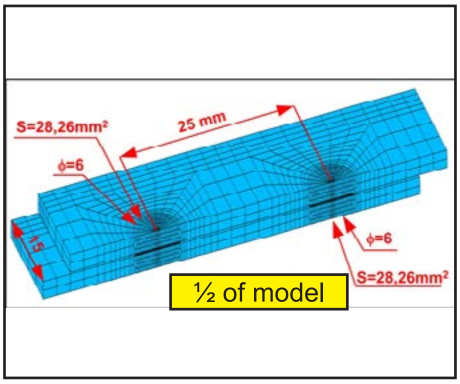

Fig. 6. Shape and dimensions of the specimen (variant M6)

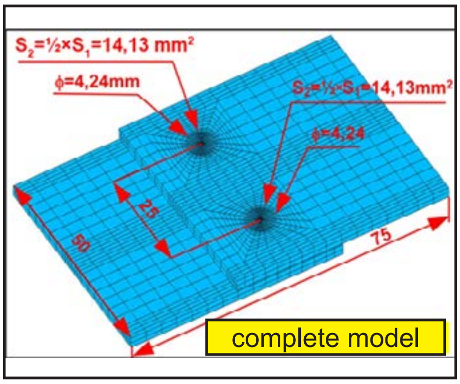

Fig. 7. Shape and dimensions of the specimen (variant M8)

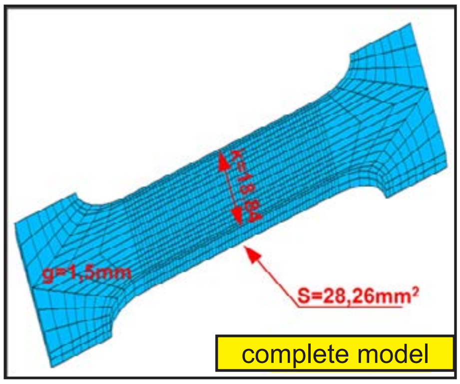

Fig. 8. Shape and dimensions of the specimen (variant M9)

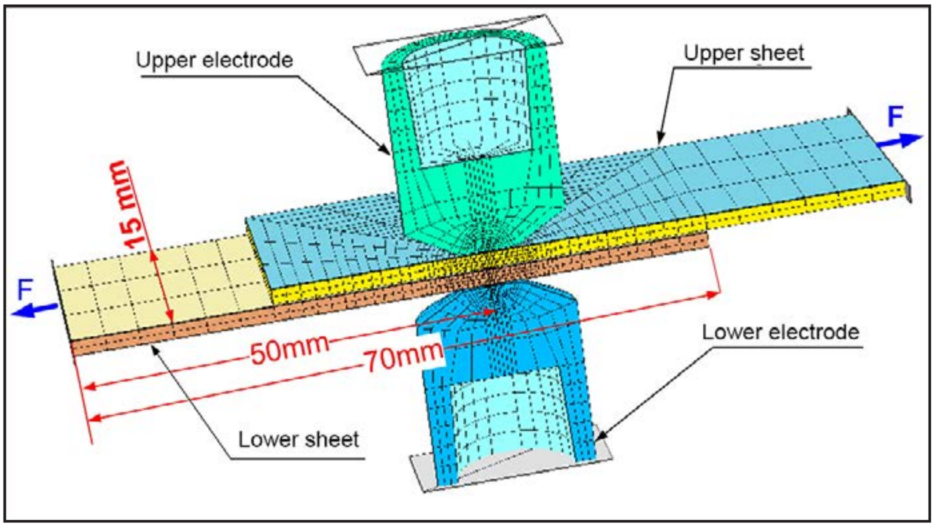

Fig. 9. Computational model (3D) in relation to the welding process and shear force in the static tensile test (variant M10 and M11)

Results of Numerical Calculations

Figures 10-11 present the selected numerical calculation results:

– shear force (F_S) in the static tensile test in relation to 11 analysed variants, i.e. various configurations, shapes and dimensions of the welded joint (Fig. 10);
– relative percentage shear force for variants M2 through M11 in relation to reference variant M1 (Fig. 11);

Figures 12 and 13 present the dependence of:

– shear force in relation to high [T] and low [M] parameters in the function of weld nugget diameter (Fig. 12);
– shear force and shear strength (R_t) in the function of weld nugget diameter in relation to the reference weld (variant M1) (Fig. 13).

Table 2 presents variants in relation to the nominal dimensions of the weld nugget area amounting to 2826 mm². In addition, in relation to variants M10 and M11 Table 2 presents welding parameters. Various values of the weld nugget diameter (2.5 mm – 6.0 mm) and, consequently, various values of the shear force (Fig. 12) were obtained as a result of various welding times set in the computational model in relation to variant M10 and M11. As regards the results presented in Figure 13 (variant M1) the shear force was calculated in numerical calculations performed also in relation to a different weld nugget (connector) diameter, in the numerical model, within the range of 2 mm to 6 mm.

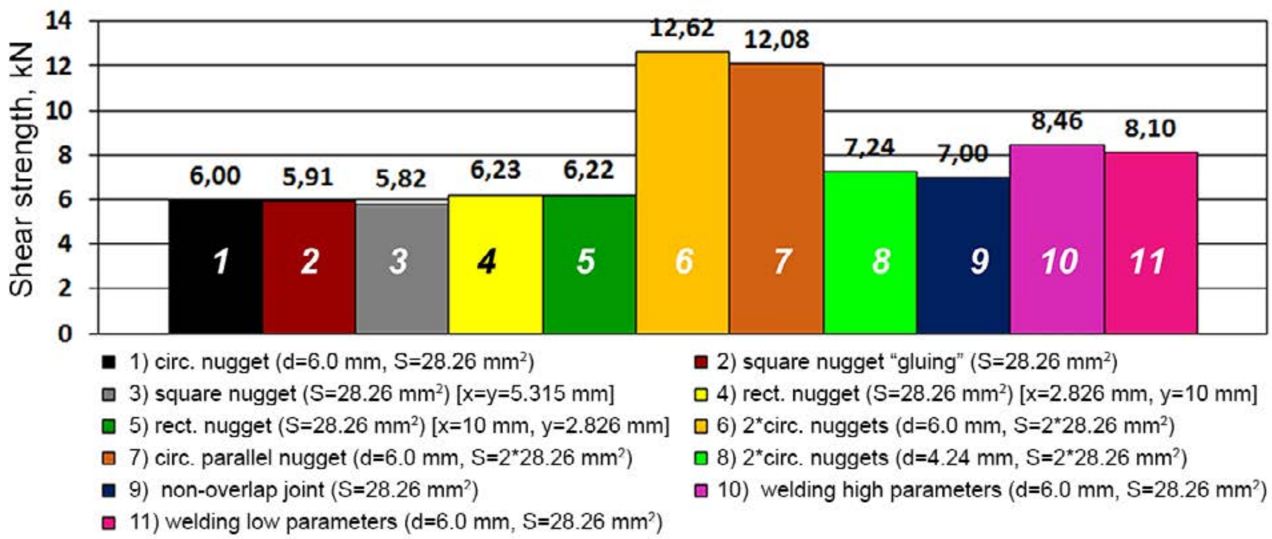

Fig. 10. Shear force in the static tensile test in relation to 11 analysed variants (FEM calculations - SORPAS)

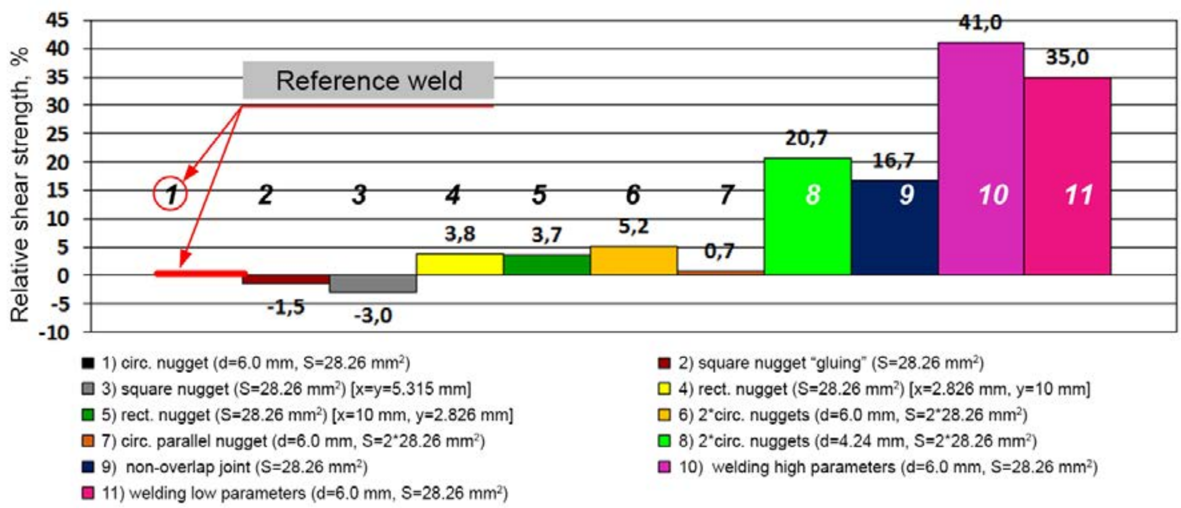

Fig. 11. Relative (percentage) in the static tensile test relation to reference variant M1 (FEM calculations - SORPAS)

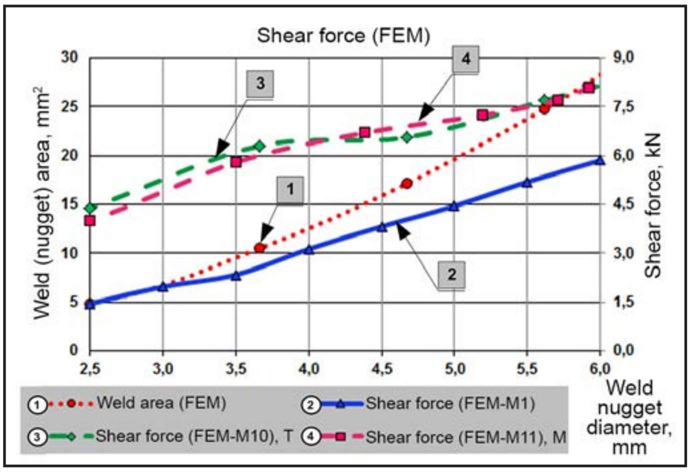

Fig. 12. Dependence of:
1) weld nugget area (FEM),
2) shear force (FEM - variant M1),
3) shear force (FEM - variant M10), high parameters [T],
4) shear force (FEM - variant M11), low parameters [M]
and the weld nugget diameter
(FEM calculations - SORPAS)

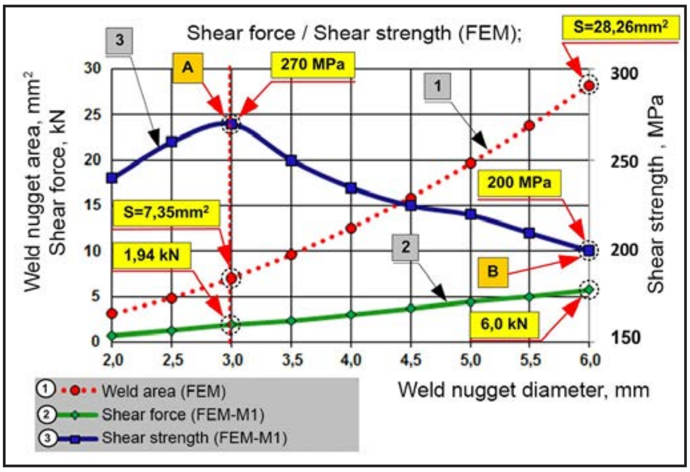

Fig. 13. Dependence of:
1) weld nugget area (FEM),
2) shear force (FEM – M1),
3) shear strength (FEM – M1),
and the weld nugget diameter
(FEM calculations – SORPAS, variant M1)

Analysis of Numerical Calculation Results

Various Weld Shapes

Figure 10 presents the shear force values obtained in the static tensile strength involving the analysed 11 variants of the ideal weld. The variant selected for reference was designated as M1 (Table 2, line 1), where the weld nugget diameter amounted to 6 mm, whereas its area was S=28.26mm². The sheets were connected by means of a 0.2 mm high connector. The additional element, i.e. the connector (area), represented the weld nugget. The analysis involved a weld nugget diameter of 6.0 mm – based on the dependence recommended when welding 1.5 mm thick sheets [2]:

$$d = 5\sqrt{g} \tag{1}$$

The shear force in relation to the above-named weld was determined in numerical calculations and amounted to F_S=6.0 kN (variant M1). Variant M1 was used as a reference when determining relative percentage differences of shear force in relation to other variants subjected to analysis and presented in Figure 11.

The highest shear force (7.24 kN) was obtained in relation to variant M8 (Table 2, line 8). In the above-named case the shear force was by approximately 21% higher than that related to reference variant M1. As regards variant M8, the test involved the shear strength in relation to the twice smaller area of a single welded joint. However, the test involved the making of two welds, each having an area of S=14.13mm². The total area of both welds was the same as the nominal weld nugget area in the reference variant (M1, S=28.26mm²). The above-named welds were made in the parallel arrangement. It appeared that the shear strength in relation to the two welds having the smaller area individually but the total area being equal to that of the reference weld area (variant M1) was higher by more than 20%.

In terms of variant M9, shear strength was tested in relation to the non-overlap joint. As regards variant M9, its cross-sectional area amounted to 28.26mm2 and was equal to the area of the weld nugget having a diameter of 6 mm (variant M1, i.e. the overlap joint). In the above-named case the shear strength was by 16% higher than that related to variant M1.

Slightly higher (yet worth mentioning) shear force (by approximately 5%) was obtained in relation to the system of two welds in the serial arrangement in relation to the direction of shear force effect (variant M6, table 2, line 6). The foregoing translated to the greater strength of the serial arrangement of welds subjected to tensile force.

The calculations concerning the shear force in relation to variants M10 and M11 involved the performance of calculations concerning the welding process (using the Sorpas software programme). Following the welding process, (numerical) calculations concerning the shear test were performed automatically. In terms of the above-named variants it was possible to observe an increase in shear force of approximately 41% and 35% in relation to high and low parameters respectively. The higher shear force resulted from the fact that the Sorpas software programme calculated the weld nugget diameter (molten area) and the above-named parameter was compared with the reference value of variant M1. In turn, the higher shear force value related to the aforesaid joint could be attributed to the greater joint area than the area of the molten material of the sheets, i.e. the weld nugget. The material outside the weld nugget was not molten but heated to high temperature and strongly plasticised. The zone outside the weld nugget formed an additional solid-state joint ring, which, once subjected to electrode force, might lead to an increase in the strength of the entire welded joint (Fig. 14).

Variants M10 and M11 demonstrated the difference of the shear force value in relation to high and low parameters, which was connected with various values concerning the heat affected zone and the indent left by the electrodes. The high and low parameters of the welding technology as well as measurement results connecting the characteristic parameters are presented in Table 3.

The analysed variants where the weld nugget shape was not circular (i.e. square and rectangular) did not reveal any significant increase in the maximum shear force (square weld nugget - variant M3, rectangular weld nugget - variant M4). In turn, variant M5, i.e. the longitudinal rectangular weld nugget revealed an increase in shear force of more than 6% (in comparison to variant M1). The increase in shear force observed in variant M5 could be ascribed to the weld elongation similar to that observed in variant M6. Further weld nugget elongation above 10.0 mm, as was the case with variant M5, triggered a further increase in shear force. However, the technological welding tests revealed the necessity of using several times higher energy parameters (higher current and longer time), which triggered the discontinuation of further numerical analysis towards the elongation of

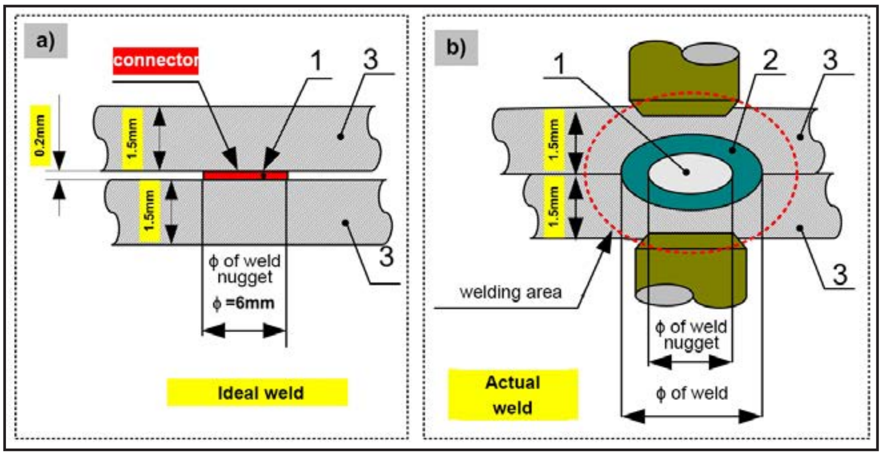

Fig. 14. Analysed welded joints:
a) ideal weld 1) weld nugget, 3) base material,
b) welded joint: 1) molten material (weld nugget), 2) heat affected zone and 3) base material

Table 3. High/low welding parameters, characteristic parameters and FEM calculation results

No.	Welding parameters	Welding current	Welding time	Force	Weld nugget diameter	Energy	Indent depth	Shear force
		kA	ms	kN	mm	kJ	mm	kN
1	high	10	160	3.0	6.0	2.0	0.13	8.46
2	low	7	410	1.5	6.0	2.8	0.10	8.10

the (rectangular) weld nugget. In technological welding tests, the making of the circular weld was significantly easier than that having the rectangular weld nugget. However, the foregoing does not prejudge the higher strength of the elongated weld nugget.

Various Weld Nugget Diameters

An increase in the diameter of the weld nugget was accompanied by an increase in its area and, consequently, strength. Figure 12 presents the values of shear force in relation to the reference weld (variant M1, curve 2) and those of shear force in relation to the welds made using the FEM calculations (variant M10 and M11, curve 3 and 4). The maximum shear force courses in relation to the ideal weld and the welds made using the FEM calculations were similar. It was possible to observe a correlation between an increase in shear force and an increase in the weld nugget diameter. However, the values of shear force were higher in relation to the computed weld (variant M10 and M11) than the ideal weld (variant M1) because of the greater joining area of the sheets (weld nugget and an additional solid state joint) (Fig. 14).

The shear strength in relation to the nominal weld nugget diameter of 6 mm amounted to R_t=200 MPa (Fig. 13, item B). In turn, the highest shear strength (R_t=270 MPa) indicated by the FEM calculations was related to the weld nugget having a diameter of 3.0 mm (Fig. 13, item A). The shear strength value related to the weld nugget having a diameter of 6 mm was by approximately 35% higher than that related to the weld nugget having a diameter of 3 mm. The obtained results justified the conclusion that the most favourable dependence in terms of shear strength per the unitary weld nugget area should amount to:

$$d = 2{,}5\sqrt{g} \tag{2}$$

In relation to dependence (2) the weld nugget area amounted to approximately 7.35 mm². It was approximately 4 times smaller than the area of the weld nugget having a diameter of 6 mm (S=28.26mm²). It should be noted that the making of a set of welds composed of, e.g. four welds having a diameter of 3 mm results in the obtainment of the same total area as that of the weld having a diameter of 6 mm. However, in the above-named case the total shear force of such a set was higher by 30% (for $4\times\phi$=3 mm F=1.95×4=7.80 kN; for $1\times\phi$=6 mm F=6.0 kN). Shear force F=1.95 kN was obtained in relation to the weld nugget having a diameter of 3 mm (Fig. 13).

Results of Experimental Tests

The lacking possibility of the direct comparison of results obtained in numerical calculations and experiments, affected by the size of the weld nugget (Fig. 14a) and that of the weld (Fig. 14b) resulted in the performance of experimental tests aimed to verify the most important and testable aspects/factors affecting the value of shear force in relation to welded joints. The tests involved the making of a series of welds (50 welds) aimed to obtain the nominal weld nugget value of 6 mm (Table 4, line 1). The aforesaid variant was recognised as the experimental reference variant (variant E2) and compared with other experimental variants. The variants related to the technological welding tests presented in Table 4 are designated using the letter E (as in *experiment*).

The shear tests performed within a static tensile test were performed in relation to:

1. base material having the same cross-sectional area as the welded joint (Table 4, line 0, variant E1),
2. overlap joint – (one) weld having a diameter of 6 mm (Table 4 line 1, variant E2) as the reference weld,
3. overlap joint – (two) welds having a diameter of 6 mm in the serial arrangement of welds (distance between welds amounted to 70 mm) (Table 4 line 2, variant E3),
4. overlap joints, in relation to one weld and increasingly shorter welding times, aimed

to obtain the increasingly smaller diameter and the area of the weld (Table 4 line 3, 4 and 5, variant E4).

The welded joints were subjected to peeling tests aimed to determine the weld diameter. The experimental test results in the form of numerical values are presented in Table 4. In turn, the dependence of the maximum shear force and of the shear strength (R_t) is presented in Figures 15 and 16.

Analysis of Experimental Results

The experimental tests confirmed the results obtained in the numerical calculations. When comparing the experimental test results concerning the reference weld (Table 4, line 1, variant E2) it was possible to observe an increase in:

1. shear force of approximately 5% (Table 4, line 2, variant E3) in relation to the two welds arranged in the serial system, parallel to the direction of the shear force effect; the diameter of each weld amounted to 6 mm;
2. shear strength (R_t), i.e. shear strength per the unitary weld area. The highest value obtained in the experimental tests was observed in relation to the weld diameter amounting to 4.1 mm (Table 4, line 4, variant E4). The highest value of shear strength was R_t=432 MPa (Fig. 15, item A). In relation to R_t=248 MPa, corresponding to the weld diameter amounting to 6.0 mm (Fig. 15, item B), the foregoing constituted an increase of approximately 74%.

The graphic presentation of the shear force (F_S) and the shear strength (R_t) of the weld in experimental conditions (Fig. 15, 16) confirmed the results obtained in the FEM calculations (Fig. 12, 13).

Comparison of Results Obtained in FEM Calculations and Experimental Tests

The comparison of the results obtained in the numerical calculations and in the experimental tests are presented in Figures 17 and 18. It is possible to observe the significant correlation of the results obtained in the numerical calculations and those of experimental tests. When comparing the shear strength and adopting the

Table 4. Parameters of technological welding tests, shear force, shear strength (welded material - sheet, g=1.5mm, DX53)

No.	Variant no.	Welding current	Welding time	Force	Weld diameter	Joint (weld) area	Remarks	Additional information	Shear force F_s	Relative shear force (E2)	Shear strength (R_t)	Relative shear strength (E2)
		kA	ms	kN	mm	mm²			kN	%	MPa	%
0	E1	---	---	---	---	28.26	base material	non-overlap joint; specimen width 18.84m (S=28.26mm²)	8.2	---	289	---
1	E2	9.0	200	2.7	6.0	28.26	nominal parameters (reference variant)	1 weld	7.0	0.0	248	0.0
2	E3	9.0	200	2.7	6.0	28.26	shearing	2 serial welds (strength per 1 weld)	7.35	5.0	260	5.0
3	E4	9.0	190	2.7	4.7	17.34	peeling	1 weld (smaller diameters)	6.4	-8.6	369	49.0
4		9.0	180	2.7	4.1	13.20	shearing	1 weld (smaller diameters)	5.7	-18.6	432	74.4
5		9.0	160	2.7	3.9	11.94	shearing	1 weld (smaller diameters)	4.0	-42.9	335	35.2

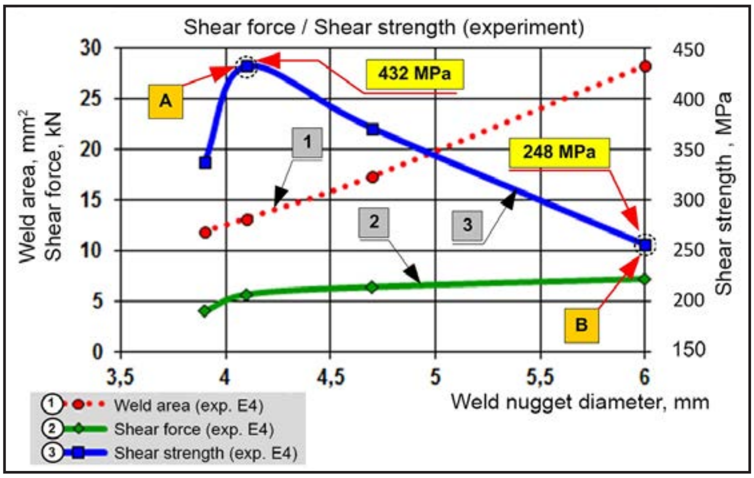

Fig. 15. Dependences of: 1) weld area (experiment E4), 2) shear force (experiment E4), 3) shear strength (experiment E4) in the technological welding test (experiment, variant E4) and the weld nugget diameter

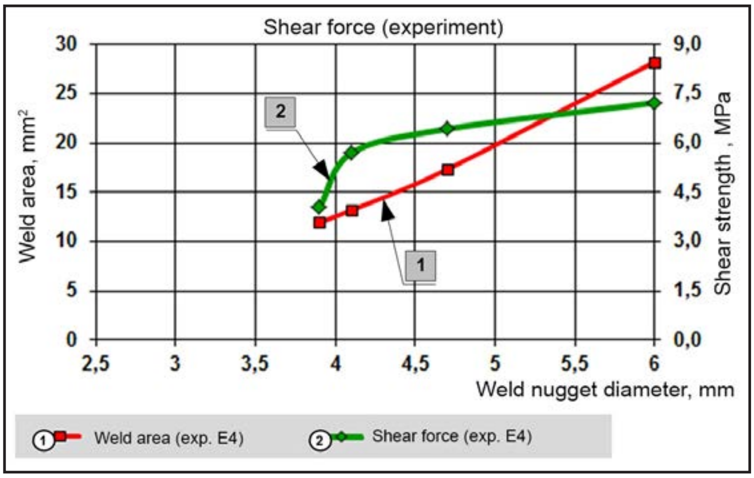

Fig. 16. Dependence of: 1) weld nugget area (experiment - variant E4), 2) shear force (experiment - variant E4), and the weld nugget diameter

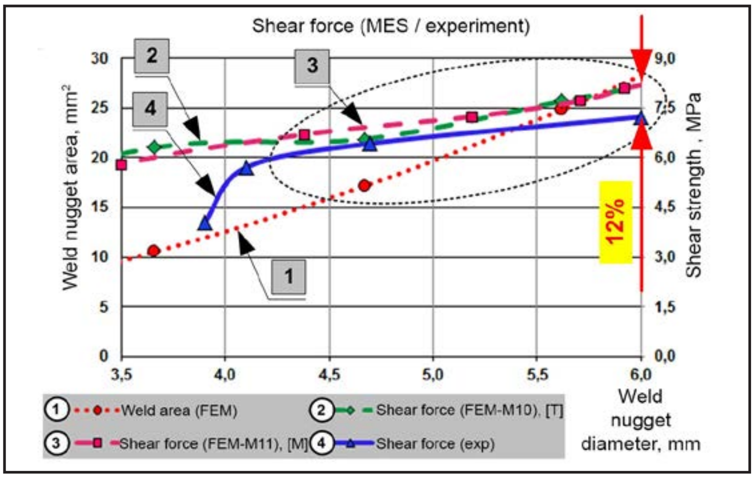

Fig. 17. Comparison of the shear strength obtained in the FEM calculations and experimental tests in relation to the weld nugget diameter: 1) weld nugget area (FEM), 2) shear strength, welding + shearing (FEM calculations, variant M10, high parameters [T]), 3) shear strength, welding + shearing (FEM calculations, variant M11, low parameters [M]), 4) shear strength, technological welding test (experiment, variant E4).

experimental results as reference, it is possible to notice in Figure 17 that the numerical calculation results (within the weld nugget diameter range of 4.2 mm to 6.0 mm) vary by approximately 10-12% (weld nugget diameter 6 mm, curve 4 as well as curves 2 and 3). The analysed shear strength values (Fig. 18) in relation to the weld diameter range of 4.5 mm to 6, 0 mm vary by a maximum of approximately 15% (curves 4 and 5).

Summary

1. The assumed objective of the tests was achieved. The tests involved the determination of the effect of the weld nugget shape (i.e. circular, square and rectangular) as well as the weld area (including the weld nugget diameter), weld systems (serial and parallel) and welding technology parameters on the weld strength in the static tensile test. The tests were performed using SORPAS-based numerical calculations and aimed to determine the shape of the ideal weld. Selected feasible variants were subjected to experimental verification. The experimental test results coincided with the numerical calculation results. Maximum differences between the FEM calculation results and the experimental results amounted to approximately 12% and 15% as regards the maximum shear force and shear strength respectively.

2. Assuming the highest value of the shear strength in the static tensile test as the primary criterion, the most favourable variants were M8 and M6.

- Variant M8 revealed an increase in shear strength in relation to two welds having a smaller weld nugget area, yet the total area equal to the reference weld area (variant M1). In the above-named variant the area of a single weld amounted to 14.13 mm² (ϕ=4,24 mm). The shear strength in relation to this joint was higher by 21% than that related to the reference variant (1). The obtained result implied that the adopted criterion (1) of the weld nugget diameter in relation to the sheet thickness was not the most favourable one. Having in mind the highest shear strength, it would be necessary to verify the selection criterion of the weld nugget diameter in relation to the sheet thickness referred to in publications [6] and [2, p. 100]. As regards the above-presented aspect, the most favourable are recommendations by the AWS (American Welding Society) [7], i.e. specified in the US standards (3), enabling the obtainment of higher shear strength.

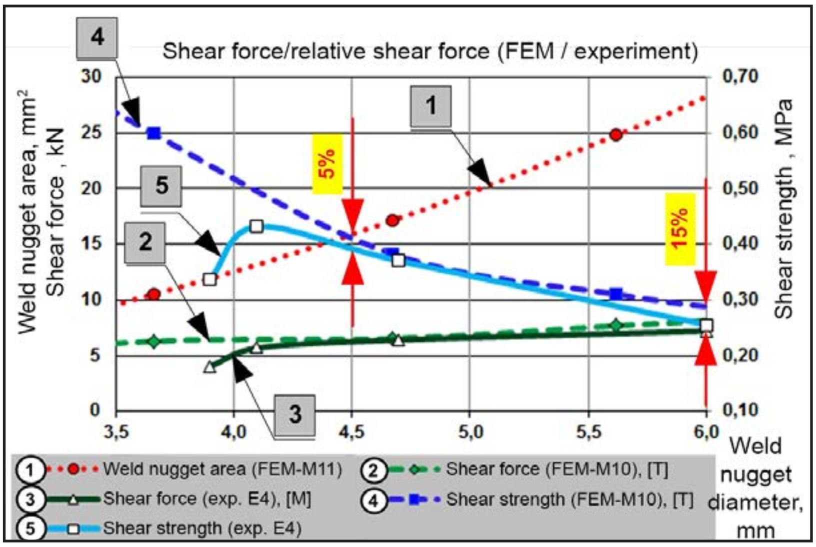

Fig. 18. Dependence of the shear force obtained in the FEM calculations and experimental tests to the weld nugget diameter: 1) weld nugget area (FEM), 2) shear force, (FEM calculations, variant M10, high parameters [T]), 3) shear force, (experiment, variant E4, high parameters [T]), 4) shear strength, (FEM calculations, variant M10, high parameters [T]), 5) shear strength, (experiment, variant E4, high parameters [T])

$$d = 4\sqrt{g} \quad (3)$$

Recommendations followed in Japan, Germany [8] or Poland [2 p. 100] (1) are characterised by a greater safety margin (in terms of the nominal weld nugget diameter), yet at the cost of lower shear strength.

- Variant M6 revealed that the reduction of the angle between the weld plane and the direction of the tensile force effect led to an increase in the shear strength of the joint. The angle grew smaller when welds were arranged in series in the direction of the tensile force effect. As regards variant M6 it was possible to observe an increase in tensile force of approximately 5%. Very similar results, including an increase in shear force by 5 %, was obtained in the experiment (Table 3, line 2, variant E3). The longitudinal shape of the weld nugget can be found in the so-called longitudinal projections or in linear welding. The weld nugget elongated in the direction of the tensile force effect is characterised by higher shear strength.

3. As expected, a significant increase in strength as regards the weld having the non-circular nugget was not obtained. The square weld nugget (variant M3) was characterised by strength similar to that of the weld having the circular nugget (variant M1).
4. In terms of the rectangular weld nugget having the longer side parallel to the direction of the tensile strength effect (also referred to as the longitudinal narrow weld nugget) it was possible to observe an increase in shear strength of more than 4% (variant M5). Similar to variant M6, the above-named increase could be ascribed to the reduction of the angle between the weld plane and the direction of the tensile force effect.
5. The ideal weld-related tests also involved the analysis of variant M9, i.e. that which was not an overlap joint. The sheet cross-sectional area was equal to the nominal weld area and amounted to 28.26 mm² (18.4 mm × 1.5 mm), whereas the shear force was higher by 16%. However, the above-presented case is not applied in the overlap welding of sheets and was subjected to analysis only for comparative purposes.
6. The performed calculations revealed that in the tensile test it is necessary to try and reduce the angle between the weld plane and the direction of shear force effect. Positive results were observed in cases of:

a) variant M5, i.e. the rectangular weld nugget – longer side parallel to the direction of the tensile force effect
b) variant M6, i.e. the serial system of welds in the direction of the tensile strength effect.

7. It was possible to observe differences of the shear force in relation to variants M10 and M11 (performed using numerical calculations), i.e. high and low parameters of welding process respectively. The shear strength in relation to the high parameters proved higher by approximately 6% and could be ascribed to the favourably narrower heat affected zone and smaller indents left by the electrodes. It is very difficult to observe differences of several percent in experimental tests, where results are often disputable. In turn, numerical models make it possible to observe even small differences amounting to several percent.

8. The research-related tests discussed in this article will be continued to determine additional parameters of the ideal weld (i.e. peel strength, torsional strength etc.) as well as to perform analysis concerning the depth of the indent left by electrodes in the material being welded.

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