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Original Research Article

Heating of electrodes during spot resistance welding in FEM calculations

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ABSTRACT

Due to the fact that many factors influence the electrode life, it is difficult to assess this impact experimentally. The study presents the analysis of the impact of individual factors on the heating of selected electrodes at specific operating parameters. The analysis was based on a SORPAS programme, intended for calculations related to resistance welding, in particular, to spot welding. In selected cases FEM calculations were verified experimentally through measurements of electrode temperature during welding cycles.

The calculations were carried out for 1 + 1 mm and 2 + 2 mm plates made of steel DX52, for hard and soft parameters. The analysis involved various designs of an electrode tip (outer diameters of electrodes of 13, 16 and 20 mm as well as a bevel angle of 60° and 120° – in case of electrodes with flat working parts, and an end radius of 50 mm – in case of spherical electrodes). The tests also concerned the impact of the "height" of an electrode working area (i.e. the distance from the cooling duct of 10.5 mm and 3 mm) on temperature distribution in an electrode.

1. Introduction

The automation of welding processes requires the use of electrodes ensuring a significant number of repeatable welds of good quality, obtained between electrode sharpening operations [1]. In the process of manufacturing of electrode materials and during their operation, one tries to obtain a long electrode life. The life of an electrode, i.e. the number of produced welds) depends on many factors which influence the behaviour of electrode material in not stabilised thermal conditions, with on-going recrystallisation and ageing. The most important factors (Fig. 1) affecting electrode life [2,3] include:

- chemical composition of an alloy used in the electrode and thermo-mechanical treatment affecting the structure, alloy hardness, softening temperature and electric conductivity,
- settings of welding parameters (pressure force, value and time of welding current) depending on the type/grade and thickness of a material being welded,
- shape and working diameter of an electrode, heating temperature of the working area, electrode cooling medium and its flow rate,
- welding rate.

In the past, the impact of the aforesaid factors on electrode life has been a subject of numerous research works [2,4–11].

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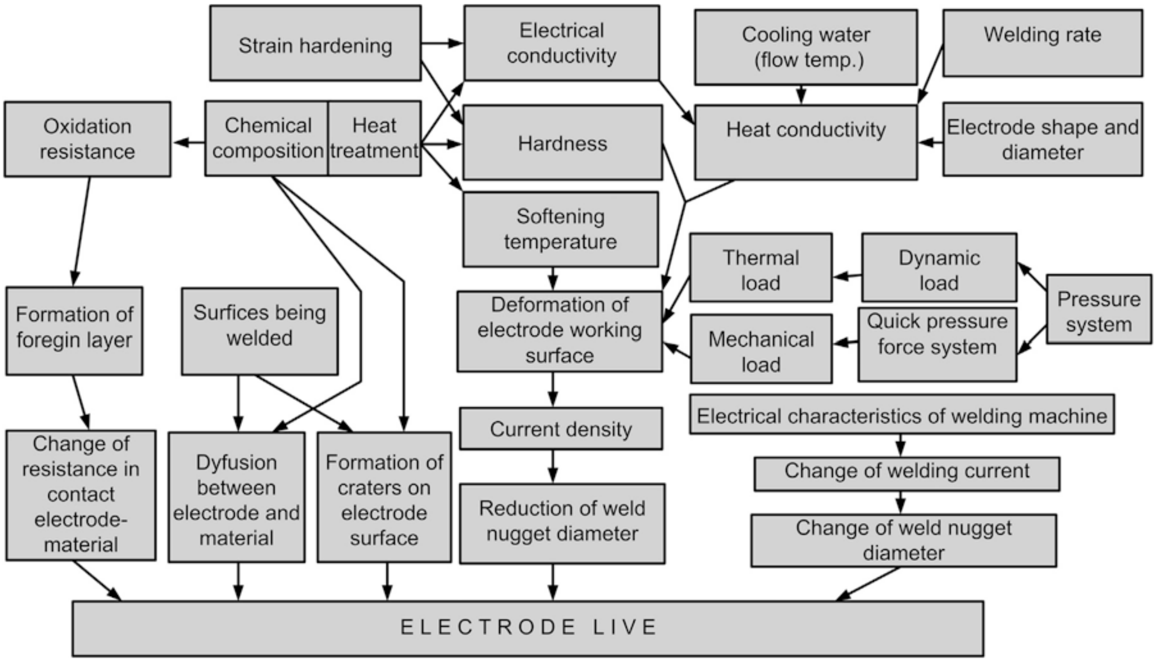


Fig. 1 – Impact of factors on electrode life in spot welding [2].

The purpose of these works was to determine the contribution of individual factors to the process of electrode wear as well as to develop principles on production and operation of electrodes. The research was based on experimentation supported by necessary equipment and software.

The alphanumeric analysis of various physical phenomena can also be used to thoroughly analyse a resistance welding process and explain phenomena which used to be difficult to examine experimentally. For many years, welding processes have been tested by means of numerical calculations [12,13]. Computational models for developing numerical calculations require many years of tests, experiments and verification. Due to interactions between electrical, thermal, mechanical and metallurgical phenomena, welding processes are highly complicated. Even ambitious and complex experimentation provides no easy method of obtaining in-depth knowledge about welding processes. For this reason, the best solution is a computational model including all possible conjugated phenomena [14,15].

Electrodes are one of more important elements of a welding process. For a long time, the impact of an electrode shape on the course of a welding process has been a subject of research [12,13]. Computational models of the past, although once considered to be quite powerful, are regarded as simplified models today. Many publications revealed that researchers focused mainly on temperature distribution in a welding area [16,17]. Scientists agreed that the use of numerical computational models could save time and reduce costs while developing new welding technologies [14,18].

Quite often, researchers must solve numerous problems related to the application of electrodes in welding processes. Mathematical analysis makes it possible to determine quantitative fractions of phenomena occurring simultaneously during a dynamic welding process. The authors of works in [19,20] concentrated on the intensification of cooling of electrodes by modifying their inner part. Other researchers analysed the influence of a cooling medium flow and an electrode working height (i.e. the distance between the active area of an electrode and the bottom of a cooling duct) on the course of a welding process [12]. Results obtained in the aforementioned investigation revealed only a little impact of these factors on a welding process. Many calculations were made by means of simplified models. Ever since, however, there has been a significant increase in a computational potential.

Many authors indicate commercial software SORPAS as characterised by experimentally verified impressive utility and computational possibilities [17,21–23]. The coincidence of experimentation and FEM calculations proved to be satisfactory.

Publication [1] enumerates factors affecting electrode life. The study discusses the issue supported by numerical calculations carried out by means of SORPAS software [24]. The authors combined their experience and expertise on electrode life obtained in previously conducted experiments [8–10] with their ability to utilise computational models [24,27] (particularly with regard to cooling intensification [28–30] as the main factor affecting electrode life. Other valuable information related to a welding process was published in [31,32].

Experiments and knowledge based on the analysis of FEM results make it possible to reduce costs related to the welding of structures as well as to obtain the greatest possible number of good-quality welds in specific welding conditions.

The use of mathematical modelling, described in this study, helped to draw conclusions as to how individual factors affect the behaviour of the working area of specific electrodes at various operation parameters. The mathematical model of electrode operation was confronted with results obtained during experimental measurements. The measurements were carried out during welding of steel plates with selected types of electrodes. The parameters applied during experimental welding were recommended by related standards [33].

2. FEM computational model

The modelling of electrodes during welding was based on software SORPAS. The programme is used for FEM simulations (calculations) of resistance welding processes, with special attention paid to spot welding [24]. A 2D model applied in the research contained approx. 2500 degrees of freedom (Fig. 2).

Calculations were carried out for spot welding of DX52 steel plates of 1 + 1 mm and 2 + 2 mm thickness and for electrodes used in welding of low-carbon steels (grade A2/2 CuCrZr,ISO 5182). A model adopted in the research concerned the building-up of a single weld, obtained with the use of hard and soft parameters. A distance between the working area of an electrode and the bottom of a cooling duct was standard, i.e. 10 mm. The research also involved testing of two other distances, i.e. 5 mm and 3 mm. The research-related analysis was conducted for various electrode designs (electrode outer diameters: 13, 16 and 20 mm; bevel angles: 60° and 120° – for electrodes with a flat working area; nose radius: 50 mm – for spherical electrodes).

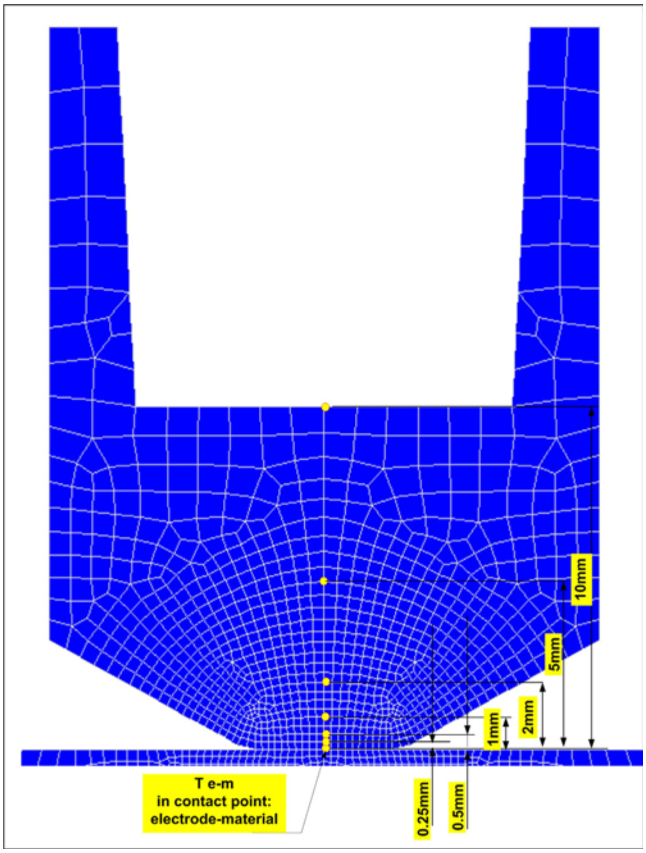


Fig. 2 – Model of (standard) upper electrode with flat working area (double-sided welding) with temperature measurement points along electrode axis: T_{em} – temperature in the contact point between an electrode and a material being welded and at a distance of 0.25; 0.5; 1.0; 2.0; 5.0 and 10 mm away from working area.

Parameters selected for modelled courses of welding of 1 + 1 mm-thick steel plates (according to instructions contained in related standards) made it possible to obtain a weld nugget diameter of 5 mm (for hard parameters) and 4 mm (for soft parameters). In turn, parameters selected for modelled courses of welding of 2 + 2 mm-thick steel plates enabled obtaining a weld nugget diameter of 7 mm (for hard parameters) and 6 mm (for soft parameters). A medium used for cooling electrodes was water (flow rate: 4 l/min, temperature: 15 °C).

The material properties of welded materials (DX52) and of electrodes (A2/2) are presented in Tables 1 and 2.

The software SORPAS used in the numerical research is developed with fully coupling of four numerical models including: electrical, thermal, metallurgical and mechanical. The special contribution of SORPAS for modelling of resistance welding is also due to the realistic modelling of contact resistance, which is essential in resistance welding. The industrial applications of SORPAS with many leading manufacturing companies worldwide have also enhanced the integration of numerical modelling with welding engineering expertise [25,26].

3. FEM calculation results

The shapes of working areas of electrodes, welding parameters and characteristic quantities obtained in FEM calculations are presented in Table 3.

One of the main factors affecting the life of electrodes is the heating temperature of the electrode working area. The temperature depends mainly on the parameters of current and the time of current flow. During electrode operation the pressure force combined with temperature (often exceeding the softening point of electrode material) causes the electrode working diameter to increase. As a result, current density and unitary pressure decrease, which, in turn, leads to the reduction of a weld nugget diameter and the deterioration of a joint strength. If the aforesaid phenomenon occurs after building up of a small number of welds, it is necessary to correct (sharpen) the working part of an electrode more often. The correction (sharpening) of an electrode consists in removing a softened layer from the working area of an electrode. The number of regenerations (i.e. sharpening) directly affects the number of welds made with a given electrode before it wears entirely.

Fig. 3 presents the results of calculations made with the SORPAS programme, illustrating changes in the weld nugget diameter during the flow of welding current. In case of hard parameters, the weld nugget obtains the nominal size (i.e. a diameter equal to the diameter of an electrode) relatively quickly. Sometimes one can even observe a weld nugget growth exceeding the size of the working diameter of an electrode. Such a phenomenon is unfavourable as it may result in the expulsion of liquid metal out of a weld nugget.

In case of soft parameters, obtaining the nominal diameter of a weld nugget is difficult or, for longer welding times, even

Table 1 – Material properties of DX52 steel.

Temperature (°C)	Thermal conductivity (W/m K)	Temperature (°C)	Heat capacity (J/kg K)	Temperature (°C)	Resistivity (μΩ m)	Temperature (°C)	Mass density (kg/m^3)	Temperature (°C)	Thermal expansion coefficient (10^{-6}/°C)	Temperature (°C)	Young's modulus of elasticity (kN/mm^2)
20	54.0	20	481	20	0.141	20	7871	100	12.6	25	200
100	48.5	150	519	100	0.200			200	13.1		
200	47.4	200	536	200	0.258			300	13.5		
400	37.0	250	553	400	0.473			400	13.8		
600	29.7	300	574	600	0.765			500	14.2		
700	27.2	350	595	700	0.931			600	14.6		
900	26.8	450	662	900	1.137			700	15.0		
1100	30.1	550	754	1100	1.185			800	14.7		
1300	33.1	650	867	1300	1.234			1000	13.8		
1500	37.2	700	1139	1500	1.240						
		750	875								
		850	846								

Table 2 – Material properties of electrode material A2/2 CuCrZr (ISO 5182).

Temperature (°C)	Thermal conductivity (W/m K)	Temperature (°C)	Heat capacity (J/kg K)	Temperature (°C)	Resistivity (μΩ m)	Temperature (°C)	Mass density (kg/m^3)	Temperature (°C)	Thermal expansion coefficient (10^{-6}/°C)	Temperature (°C)	Young's modulus of elasticity (kN/mm^2)
20	326.3	20	420	20	0.022	20	8890	25	16.5	25	117
100	342.1	127	446	100	0.027	1080	8320				
300	338.1	327	466	200	0.038						
500	340.3	527	482	300	0.042						
700	332.0	727	500	400	0.049						
900	321.8	927	529	500	0.057						
				600	0.065						
				700	0.073						
				800	0.082						
				900	0.091						
				1000	0.102						
				1100	0.220						
				1200	0.227						
				1300	0.223						

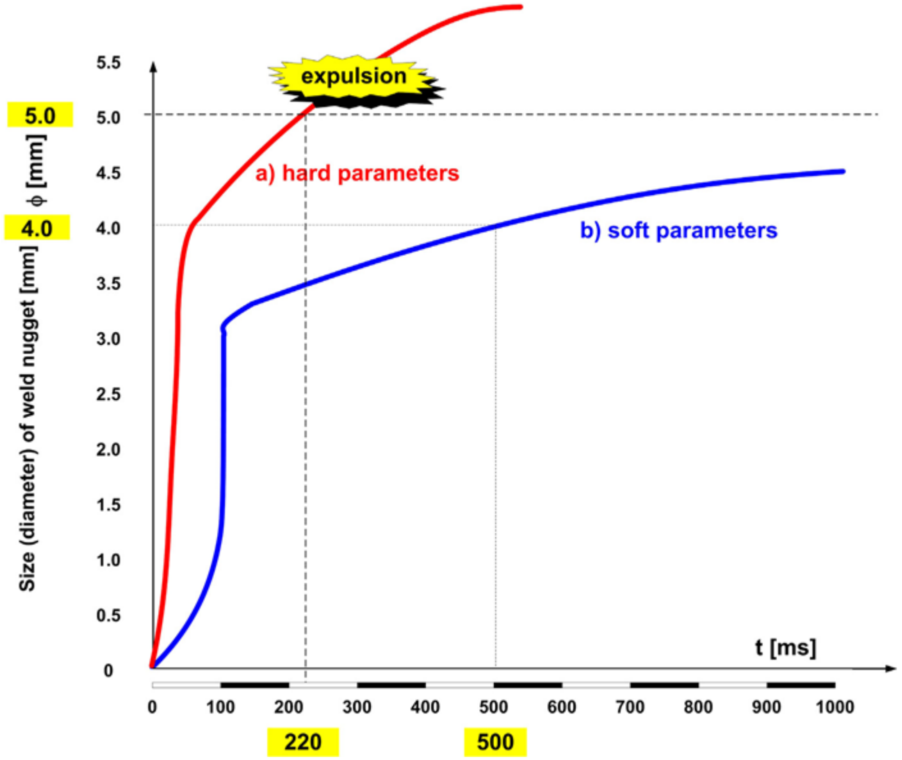


Fig. 3 – Simulation of growth of weld nugget diameter for steel plates DX52 of thick: 1 + 1 mm with the use of using hard and soft welding parameters. (a) Hard parameters and (b) soft parameters.

impossible. This effect is due to less advantageous thermal conditions, i.e. the dominance of harmful heat of losses (flow of heat towards electrodes and materials being welded) over the useful heat (Joule heat) responsible for the formation of a weld nugget.

Further figures present simulation results, combining temperatures of heating, softening areas and welding parameters. A softening point assumed for an electrode material amounted to 485 °C.

Calculated values of temperature (Fig. 4) on the surface of electrodes do not exceed 800 °C and 900 °C respectively; the depth of a softening area is approx. 1.2 mm and 1.8 mm. The intersection of a line representing the softening point of electrode material (485 °C) with a curve of heating temperature indicates the depth of a softening area.

3.1. *Results of FEM calculations – analysis of course of heating temperature in electrode*

Temperature in the vicinity of a cooling duct is contained within a range of 40–50 °C. The calculations were made for a 10 mm distance between the active area of an electrode and the bottom of a cooling duct. The aforesaid distance of 10 mm is typical of new electrodes.

For comparison, Fig. 5a and b presents calculation results for soft parameters.

Figs. 4a,b and 5a,b present results obtained for the 1 + 1 mm plates welded with the use of hard and soft parameters. The electrode had an outer diameter of 20 mm and the bevel angles of 120° and 60°.

FEM-calculated values of temperature (Fig. 5a and b) on the surface of electrodes do not exceed 530 °C and 620 °C respectively; the depth of a softening area is approx. 0.25 mm and 0.8 mm.

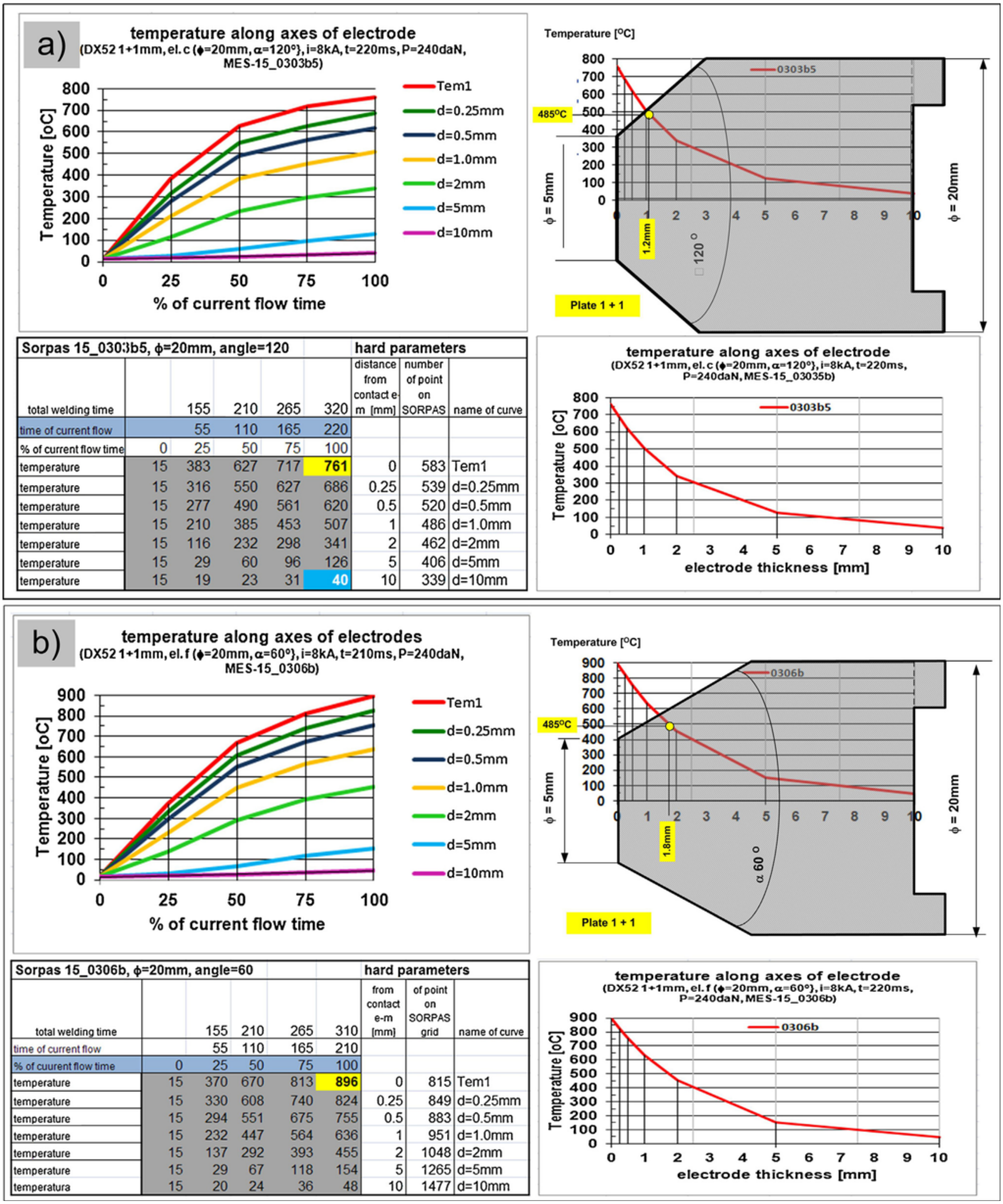
Lower temperature values cause smaller changes in the subsurface of electrode material.

Similar calculations as those made for Figs. 4a,b and 5a,b were carried out for electrodes with an outer diameter of 16 mm and bevel angles of 120° and 60°, both for hard and soft parameters (see Appendix, Fig. 11a,b and c,d).

The calculation results concerning the heating of spherical electrodes during the welding of 1 + 1 mm-thick plates are presented in Fig. 5c and d. The analysis of calculations with the use of hard welding parameters revealed the depth of a softening area of 0.8 mm and a surface temperature of 665 °C. The maximum temperature is 100 °C lower than in the case of flat electrodes with a diameter of 20 mm (Figs. 4a and 5c respectively).

The operation of electrodes requires their sharpening. As a result, the height of a working part decreases. In the model under discussion the analysis concerned the heating 5 mm- and 3 mm-high working parts (Fig. 5e and f). A decrease in the height of a working part is responsible for changes of cooling conditions. Irrespective of the height of a working element, the flow of cooling water was 4 l/min.

Simulation results presented in Fig. 4 and (Fig. 5e and f) reveal a very similar heating temperature of electrode tips (approx. 760 °C) when their height amounted to 10 mm and 5 mm. It should be noted that the mass of the 5 mm-high electrode tip decreased significantly. It was also possible to observe a change



Sorpas 15_0303b5, ϕ=20mm, angle=120						hard parameters		
total welding time		155	210	265	320	distance from contact e-m [mm]	number of point on SORPAS	name of curve
time of current flow		55	110	165	220			
% of current flow time	0	25	50	75	100			
temperature	15	383	627	717	761	0	583	Tem1
temperature	15	316	550	627	686	0.25	539	d=0.25mm
temperature	15	277	490	561	620	0.5	520	d=0.5mm
temperature	15	210	385	453	507	1	486	d=1.0mm
temperature	15	116	232	298	341	2	462	d=2mm
temperature	15	29	60	96	126	5	406	d=5mm
temperature	15	19	23	31	40	10	339	d=10mm

Sorpas 15_0306b, ϕ=20mm, angle=60						hard parameters		
total welding time		155	210	265	310	from contact e-m [mm]	of point on SORPAS grid	name of curve
time of current flow		55	110	165	210			
% of cuurent flow time	0	25	50	75	100			
temperature	15	370	670	813	896	0	815	Tem1
temperature	15	330	608	740	824	0.25	849	d=0.25mm
temperature	15	294	551	675	755	0.5	883	d=0.5mm
temperature	15	232	447	564	636	1	951	d=1.0mm
temperature	15	137	292	393	455	2	1048	d=2mm
temperature	15	29	67	118	154	5	1265	d=5mm
temperatura	15	20	24	36	48	10	1477	d=10mm

Fig. 4 – Temperature of heating of electrode tip with outer diameter of 20 mm and bevel angle of (a) 120° and (b) 60° as well as depth of softening areas during welding of 1 + 1 mm-thick plates with the use of *hard parameters* of welding.

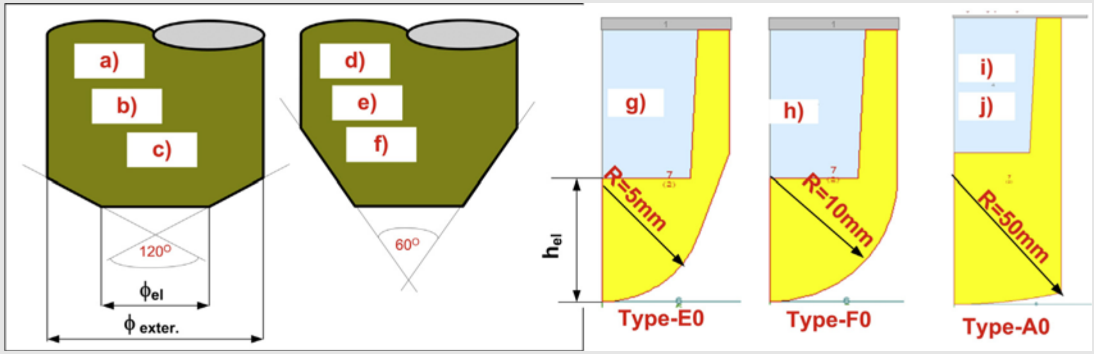
in the cooling conditions of the 10 mm-high working part (of the electrode not sharpened). A reduction of the height of a working part to 3 mm (after many regenerations, i.e. sharpening) resulted in a slightly changed heating temperature of an electrode working area during welding (718 °C). The calculations and results, however, concern the welding technology with hard parameters and a welding time of only 220 ms. Results for soft parameters are presented in Appendix (see Fig. 11i and j).

Table 3 – Welding parameters and characteristic quantities obtained in FEM calculations.

Parameters:

- material: DX52 (1 mm + 1 mm), (2 mm + 2 mm)
- electrodes:

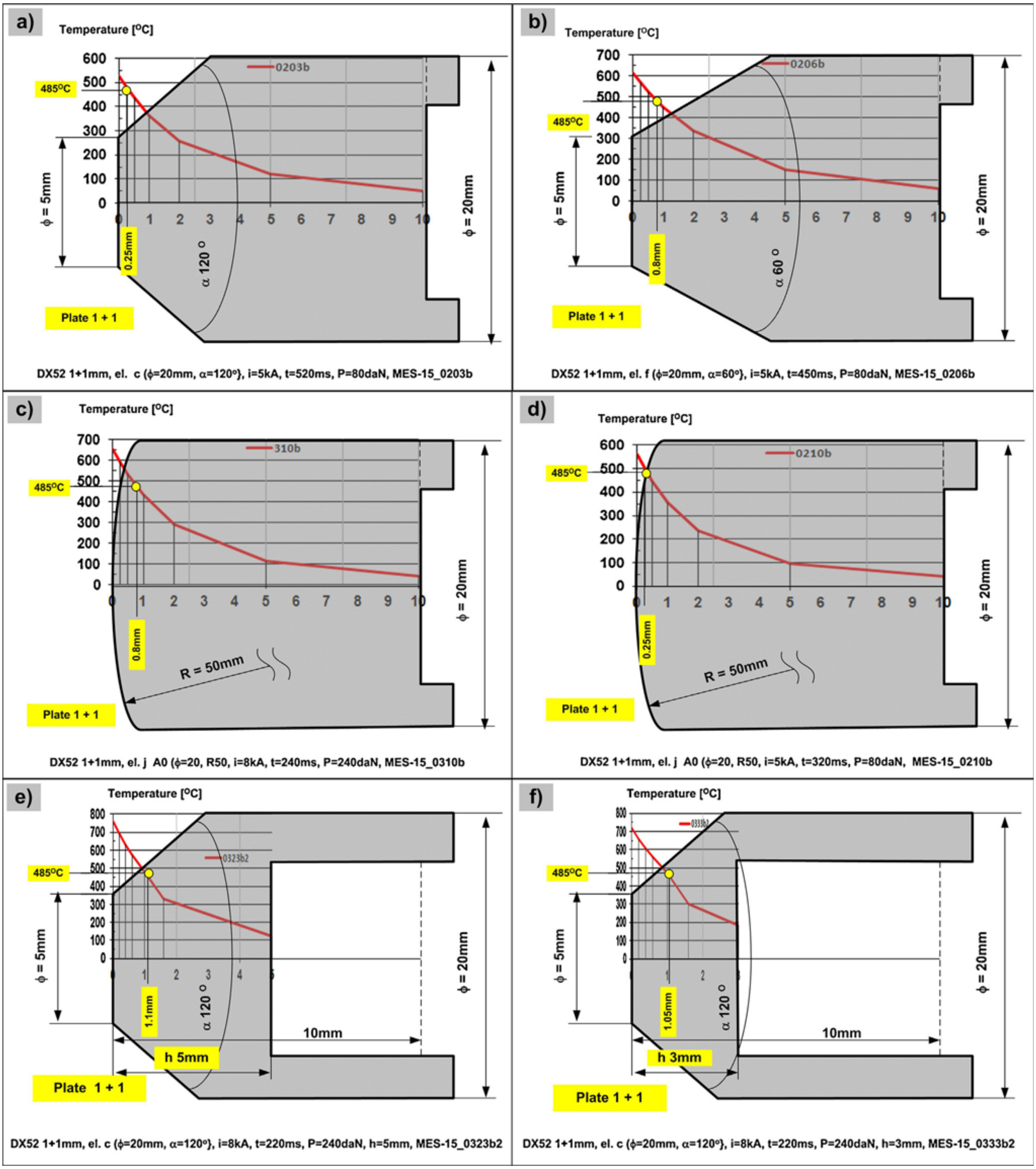
1. (a) B0, $\phi_{el} = 5$ mm, $\phi_{exter.} = 13$ mm, $\alpha = 120^\circ$
2. (b) B0, $\phi_{el} = 5$ mm, $\phi_{exter.} = 16$ mm, $\alpha = 120^\circ$
3. (c) B0, $\phi_{el} = 5$ mm, $\phi_{exter.} = 20$ mm, $\alpha = 120^\circ$
4. (d) B0, $\phi_{el} = 5$ mm, $\phi_{exter.} = 13$ mm, $\alpha = 60^\circ$
5. (e) B0, $\phi_{el} = 5$ mm, $\phi_{exter.} = 16$ mm, $\alpha = 60^\circ$
6. (f) B0, $\phi_{el} = 5$ mm, $\phi_{exter.} = 20$ mm, $\alpha = 60^\circ$
7. (g) E0, $\phi_{exter.} = 13$ mm, R = 5 mm
8. (h) F0, $\phi_{exter.} = 20$ mm, R = 10 mm
9. (i) A0, $\phi_{exter.} = 13$ mm, R = 30 mm
10. (j) A0, $\phi_{exter.} = 20$ mm, R = 50 mm



No.	Name of set	Electrode type $\phi_{exter.}$ angle of bevel	Welding parameters i (kA)/P (daN)/t (msl)	Flow (l/min)/ temp. of water (°C)	Weld nugget volume (mm^3)	Welding time (ms)	Energy (J)	Nodes T_{j1}/T_{em1}	Indent (mm)	T_{j1} (temperature in weld nugget) (°C)	T_{em1} (temp. in contact electrode-material) (°C)	Weld nugget diameter (mm)	Remarks
1 + 1 mm; soft parameters: 5 kA, 80 daN													
1	0201b	a/13/120	5.0/80/500	4.0/15	11.7	500	1938	783/574	0.01	1774	594	4.0	
2	0202b	b/16/120	5.0/80/490	4.0/15	11.2	490	1867	673/538	0.01	1757	579	4.0	
3	0203b	c/20/120	5.0/80/520	4.0/15	11.5	520	1963	673/561	0.01	1776	571	4.0	
4	0204b	d/13/60	5.0/80/430	4.0/15	12.4	430	1702	622/819	0.01	1800	654	4.0	
5	0205b	e/16/60	5.0/80/410	4.0/15	13.1	410	1620	666/822	0.01	1800	700	4.0	
6	0206b	f/20/60	5.0/80/450	4.0/15	12.5	450	1750	653/778	0.01	1785	656	4.0	
7	0207b	g/13/R5	5.0/80/160	4.0/15	21.1	160	1137	539/727	0.36	>2200	>1000	4.0	$t_{weld} = 35$ ms, $T_{j1} > 2200$ °C $t_{weld} = 7$ ms, $T_{em1} > 1000$ °C
8	0208b	h/20/10	5.0/80/220	4.0/15	22.0	220	1374	574/541	0.20	>2200	985	4.0	$t_{weld} = 37$ ms, $T_{j1} > 2200$ °C
9	0209b	i/13/R30	5.0/80/240	4.0/15	18.5	240	1356	585/758	0.06	>2200	667	4.0	$t_{weld} = 66$ ms, $T_{j1} > 2200$ °C
10	0210b	j/20/R50	5.0/80/320	4.0/15	16.8	320	1600	594/689	0.04	>2200	605	4.0	$t_{weld} = 97$ ms, $T_{j1} > 2200$ °C
1 + 1 mm; hard parameters: 8 kA, 240 daN													
11	0301b	a/13/120	8.0/240/220	4.0/15	26.4	220	1783	783/574	0.10	2115	787	5.0	
12	0302b	b/16/120	8.0/240/220	4.0/15	26.8	220	1753	673/538	0.10	2109	779	5.0	
13a	0303b	c/20/120	8.0/240/220	4.0/15	27.9	220	1769	673/561	0.14	2187	803	5.0	
13b	0303b5	c/20/120 M	8.0/240/220	4.0/15	27.4	220	1744	695/560	0.10	2155	761	5.1	
14	0304b	d/13/60	8.0/240/220	4.0/15	28.3	220	1815	622/819	0.12	2125	897	5.0	
15	0305b	e/16/60	8.0/240/210	4.0/15	28.2	210	1730	666/822	0.12	2130	949	5.0	
16	0306b	f/20/60	8.0/240/210	4.0/15	28.5	210	1722	653/778	0.14	2162	903	5.0	
17	0307b	g/13/R5	8.0/240/130	4.0/15	21.2	130	1414	539/727	0.70	>2200	>1000	5.0	$t_{weld} = 35$ ms, $T_{j1} > 2200$ °C $t_{weld} = 56$ ms, $T_{em1} > 1000$ °C
18	0308b	h/20/10	8.0/240/220	4.0/15	28.4	220	1963	574/541	0.40	>2200	920	5.0	$t_{weld} = 56$ ms, $T_{j1} > 2200$ °C
19	0309b	i/13/R30	8.0/240/210	4.0/15	26.0	210	1822	585/758	0.13	>2200	762	5.0	$t_{weld} = 97$ ms, $T_{j1} > 2200$ °C
20	0310b	j/20/R50	8.0/240/240	4.0/15	24.0	240	1856	594/689	0.09	2080	667	5.0	

1 + 1 mm; height of electrode working area (h_{el}) 5 and 3 mm (hard parameters)													
29a	0323b	d/20/120/5	8.0/240/220	4.0/15	27.4	220	1751	702/554	0.14	2160	801	5.1	h_{el} = 5 mm
29b	0323b2	d/20/120/M	8.0/240/220	4.0/15	26.3	220	1726	658/521	0.11	2123	761	5.1	h_{el} = 5 mm
30a	0323b	d/20/120/3	8.0/240/220	4.0/15	27.9	220	1776	580//799	0.14	2133	762	5.1	h_{el} = 3 mm
30b	0323b2	d/20/120/M	8.0/240/220	4.0/15	25.8	220	1747	631/846	0.26	2015	718	5.0	h_{el} = 3 mm
1 + 1 mm; increase in electrode working diameter (hard parameters)													
31	0303b2	c/20/120	8.0/240/220	4.0/15	24.8	220	1612	657/735	0.07	2022	700	4.9	ϕ_{el} = 5.5 mm (+10%)
32	0303b3	c/20/120	8.0/240/220	4.0/15	17.4	220	1439	671/752	0.03	1817	585	4.6	ϕ_{el} = 6.0 mm (+20%)
33	0303b4	c/20/120	8.0/240/220	4.0/15	9.9	220	1306	736/631	0.01	1658	499	4.4	ϕ_{el} = 6.5 mm (+30%)
1 + 1 mm; increase in electrode working diameter (soft parameters)													
34	0203b2	c/20/120	5.0/80/520	4.0/15	4.0	520	1767	657/735	0.01	1584	462	3.4	ϕ_{el} = 5.5 mm(+10%)
35	0203b3	c/20/120	5.0/80/520	4.0/15	2.3	520	1719	671/752	0.01	1541	453	3.3	ϕ_{el} = 6.0 mm (+20%)
36	0203b4	c/20/120	5.0/80/520	4.0/15	0.1	520	1653	736/631	0.01	1453	404	0.2	ϕ_{el} = 6.5 mm (+30%)
2 + 2 mm; hard parameters 12 kA, 480 daN and soft parameters 7.0 kA, 160 daN													
37	3001b	c/20/120	12/480/360	4.0/15	108.0	360	5304	648/448	0.22	2136	685	7.0	
38	3002b	f/20/60	12/480/360	4.0/15	113.0	360	5429	589/953	0.25	2141	821	7.0	
39	4001b	c/20/120	7.0/160/1000	4.0/15	69.0	1000	6339	648/448	0.07	1932	577	6.0	
40	4002b	f/20/60	7.0/160/920	4.0/15	71.4	920	5871	589/953	0.08	1937	649	6.0	
2 + 2 mm; increase in electrode working diameter (hard/soft parameters)													
41	3001b2	c/20/120	12/480/360	4.0/15	98.8	360	4917	650/980	0.16	2017	618	6.9	ϕ_{el} = 7.7 mm (+10%)
42	3001b3	c/20/120	12/480/360	4.0/15	75.4	360	4258	668/994	0.09	1828	523	6.6	ϕ_{el} = 8.4 mm (+20%)
43	3001b4	c/20/120	12/480/360	4.0/15	59.0	360	3980	710/998	0.06	1738	464	6.5	ϕ_{el} = 9.1 mm (+30%)
44	4001b2	c/20/120	7.0/160/1000	4.0/15	39.2	1000	5594	650/980	0.03	1737	462	5.5	ϕ_{el} = 7.7 mm(+10%)
45	4001b3	c/20/120	7.0/160/1000	4.0/15	10.0	1000	4969	668/994	0.02	1568	378	4.2	ϕ_{el} = 8.4 mm (+20%)
46	4001b4	c/20/120	7.0/160/1000	4.0/15	5.2	1000	4855	710/998	0.02	1536	372	3.8	ϕ_{el} = 9.1 mm (+30%)
1 + 1 radial electrode (hard/soft parameters)													
47	0310b	j/20/R50	8.0/240/240	4.0/15	24.0	240	1856	611/717	0.09	2071	655	5.0	
48	0210b	j/20/R50	5.0/80/320	4.0/15	16.8	320	1600	611/717	0.04	>2200	596	4.0	t_{weld} = 97 ms, $T_{j1} > 2200$ °C

T_{max} – maximum temperature in a welding area, h_{el} – electrode height, i.e. distance between the active area of an electrode and the bottom of a cooling duct, ϕ_{el} – diameter of the active area of an electrode, $\phi_{exter.}$ – diameter of the outside of an electrode.



DX52 1+1mm, el. c (ϕ=20mm, α=120°), i=5kA, t=520ms, P=80daN, MES-15_0203b

DX52 1+1mm, el. f (ϕ=20mm, α=60°), i=5kA, t=450ms, P=80daN, MES-15_0206b

DX52 1+1mm, el. j A0 (ϕ=20, R50, i=8kA, t=240ms, P=240daN, MES-15_0310b

DX52 1+1mm, el. j A0 (ϕ=20, R50, i=5kA, t=320ms, P=80daN, MES-15_0210b

DX52 1+1mm, el. c (ϕ=20mm, α=120°), i=8kA, t=220ms, P=240daN, h=5mm, MES-15_0323b2

DX52 1+1mm, el. c (ϕ=20mm, α=120°), i=8kA, t=220ms, P=240daN, h=3mm, MES-15_0333b2

Fig. 5 – Temperature of heating of electrode with outer diameter of 20 mm. (a, b) electrode tip and bevel angle of (a) 120° and (b) 60° as well as the depth of softening areas during welding with the use of *soft parameters* of welding, (c, d) working part of the spherical electrode having a radius of 50 mm and an outer diameter of 20 mm during welding with the use of (c) *hard* and (d) *soft parameters* of welding. (e, f) Electrode in the case of (e) 5 mm and (f) 3 mm height of the working part. Thickness of plates: 1 + 1 mm.

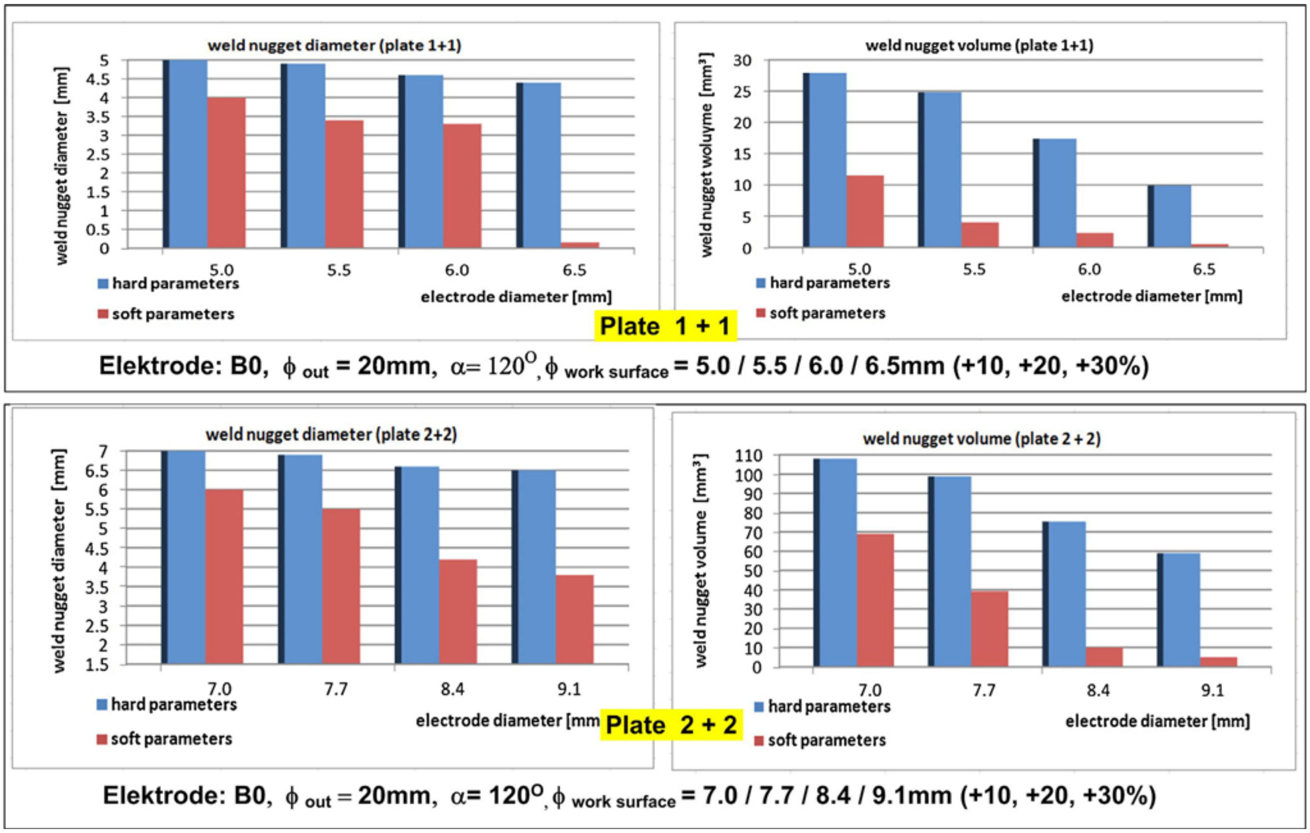


Fig. 6 – Change of weld nugget diameter and volume during welding of 1 + 1 mm and 2 + 2 mm steel plates with the use of hard and soft welding parameters.

3.2. *Results of FEM calculations – increase in diameter of electrode working area*

An important welding-related issue is a change of a weld nugget diameter caused by an increase in an electrode working diameter. This phenomenon is connected with an increasing number of built-up welds. The results of conducted simulations present an impact of 10%, 20% and 30% electrode diameter growth on a change of weld nugget diameter and volume (Fig. 6).

The results obtained for the welding of 1 + 1 mm plates with the use of hard parameters revealed that an increase in an electrode diameter of 20% decreases a weld nugget diameter by between 4.5 mm and 5 mm and, consequently, reduces the area of a weld by 20%. An increase of an electrode diameter by 30% reduces a weld nugget diameter to 4.4 mm. A weld obtained in such a process is still acceptable, but represents the quality level B.

Welding with the use of soft parameters, by means of an electrode with a 20% bigger diameter causes a significant reduction of a weld nugget diameter (i.e. between 3.3 mm and 4 mm) as well as a decrease in a weld area of 33%. A further increase in an electrode active area (from 5 mm to 6.5 mm) leads to the absence of a liquid nugget. In such case, a weld will be formed without the penetration of materials being welded, i.e. a solid state joint will be formed.

An increase in an electrode diameter leads to a decrease in a weld nugget diameter, which results in a reduction of weld strength.

Similar courses of changes of weld nugget diameters and volumes could be observed during the welding of 2 + 2 mm plates with the use of hard welding parameters. A 20% change of electrode diameter reduces a weld area by approx. 13%. The use of soft welding parameters reduces a weld area by almost 50%.

In case of the use of soft parameters, welding of 2 + 2 mm plates proves more convenient than welding of 1 + 1 mm plates. An increase in an electrode active area by 30% results in a weld nugget decrease of 37% (from 6 mm to 3.8 mm). Yet, it does not cause a complete disappearance of a molten nugget.

Thermal conditions improve with the thickness of plates being welded. Welding of thin plates, especially in case of soft parameters, results in a thermal equilibrium. The heat of losses (supplied to welds and a material being welded) and Joule heat compensate each other, which hinders or even prevents the correct expansion of a weld nugget.

4. Experimental results

Calculated heating temperatures were compared with results obtained by means of a measurement station [8] presented in

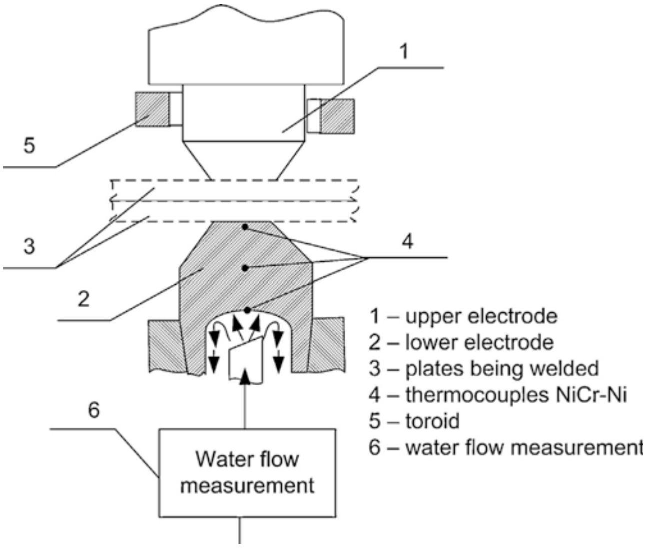


Fig. 7 – Layout of station for electrode temperature measurements during welding of steel plates.

Fig. 9. Temperature of electrodes was measured with NiCr–Ni thermocouples (0.2 mm in diameter). The aforesaid thermocouples enable obtaining accurate measurements up to 1000 °C. Three thermocouples were welded to the working area of electrodes. A thermocouple located under the working area of an electrode was 0.5 mm away from the electrode surface. A thermocouple located in the middle was 5 mm away from the electrode surface. A thermocouple in the vicinity of a cooling duct was approx. 0.5 mm from the bottom of the duct.

The layout of station for electrode temperature measurements during welding of steel plates is presented in Fig. 7.

The chemical composition of the workpieces and that of electrodes are given in Tables 4 and 5.

Table 4 – Chemical composition of welded material (DX52).

Steel grade	C max	Mn max	P max	S max	Ti and/or NB max
DX51 D – DX57 D	0.12	0.60	0.045	0.045	0.30

Table 5 – Chemical composition of electrode (A2/2).

Electrode type	Cr max	Zr max	Cu max
A2/2	0.65	0.05	99.1

Temperature measurements during the welding of 1 + 1 mm steel plates (Fig. 8) and 2 + 2 mm steel plates (Fig. 9) were carried out by means of a multi-channel oscillograph.

The comparison of FEM calculation results and resistance welding technological test results was performed for the point located 0.25 mm away from the electrode work surface.

For the thickness of welded plates (1 + 1 mm), for FEM calculation results $T_{em1(0.25mm)} = 686$ °C (Fig. 4a, file number *0303b5*) and for the technological welding test $T_{em1(0.25mm)} = 540$ °C (Fig. 8). The temperature difference amounts to 146 °C (21% less than in FEM calculations).

This result is caused by a few factors:

(a) extended welding time in numerical calculations (220 ms) was longer than the time in welding technological tests (160 ms) by 60 ms that is, by 27% (time was extended in order to obtain the nominal weld nugget diameter of 5 mm),

(b) accuracy of thermocouple location in the electrode. The FEM calculation results indicate that the temperature difference over the distance of 0.5 mm can amount to as much as 141 °C ($T_{em1} = 761$ °C, $T_{em1(0.5mm)} = 620$ °C).

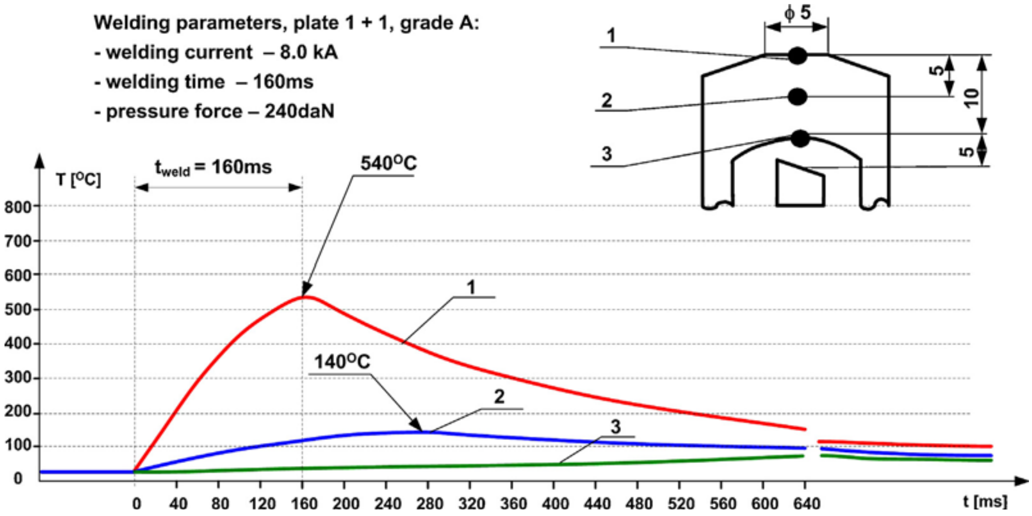


Fig. 8 – Course of changes of temperature of electrode tip during welding of 1 + 1 mm steel plates with hard parameters: current 8 kA, welding time (t_z) 0.16 s, final pressure time (t_p) 1 s, electrode pressure 240 daN, temperature measurement points 1, 2, 3.

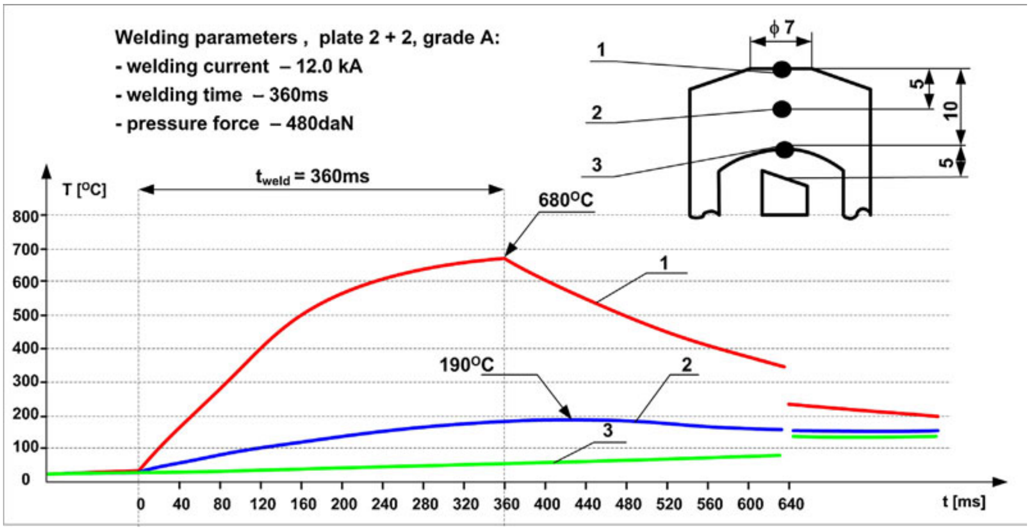


Fig. 9 – Temperatures of heating of electrodes during welding of 2 + 2 mm steel plates with the use of hard welding parameters obtained on measurement station; 1, 2, 3 – temperature measurement points.

For the greater distance from the electrode work surface temperature differences are significantly lower both for $h_{el} = 5$ mm, i.e. 14 °C (for FEM calculation results $T_{em1(5.0mm)} = 126$ °C, Fig. 4a, file number *0303b5*) and for the technological welding test ($T_{em1(5.0mm)} = 140$ °C, Fig. 10). For $h_{el} = 10$ mm temperature values are identical.

For the thicknesses of welded Plates 2 + 2 mm for FEM calculation results $T_{em1(0.25mm)} = 626$ °C (Fig. 11e and f, file number *3001b*) and for the welding technological test $T_{em1(0.25mm)} = 680$ °C (Fig. 9). The temperature difference amounts to 54 °C (8%) and is satisfactory. This result is affected by the factors presented above.

The analysis of the numerical calculation results and of experimental test results (welding technological tests) indicates that the character of temperature changes is similar. Greater accuracy (convergence) of results is observed for the greater thickness (2 + 2 mm) of welded plates. In turn, the accuracy of measurement is significantly influenced by the precise location of the thermocouple in the electrode.

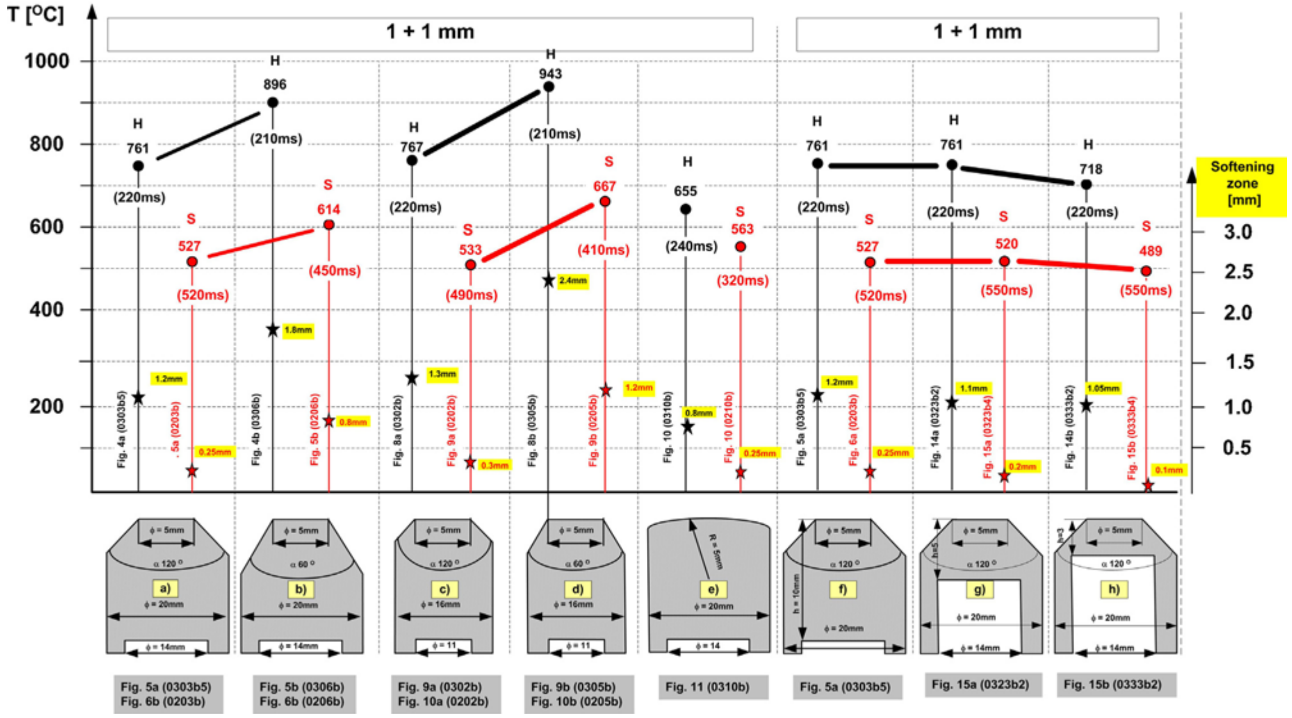


Fig. 10 – Shapes of electrode tips, welding parameters and characteristic quantities obtained in computational model (H – hard welding parameters, S – soft welding parameters).

For the greater distance from the electrode work surface temperature differences are significantly lower both for $h_{el} = 5$ mm, i.e. 15 °C (for FEM calculation results $T_{em1\,(5.0mm)} = 175$ °C, Fig. 11e, file number *3001b*) and for the technological welding test ($T_{em1(5.0mm)} = 190$ °C, Fig. 8). For $h_{el} = 10$ mm temperature values are identical.

5. Summary

The main purpose of FEM calculations was the modelling of electrode operating conditions (during welding of steel plates) and the determination of factors for proper electrode operation. The research assumed soft and hard welding parameters, commonly applied in welding of steel plates, as well as basic design solutions of an electrode tip. Two bevel angles (120 °C and 60 °C) and two outer electrode diameters (20 mm and 16 mm) were analysed within the research. It was also necessary to take into consideration the softening area of an electrode (important from regeneration point of view) and a decreasing distance between the working area and the bottom of a cooling duct (resulting from electrode operation). After adopting a softening point (485 °C) (from the range 475 °C to 500 °C) of materials used for electrodes applied in welding of steel plates, it was possible (in combination with the heating temperature of an electrode tip) to determine the depth of a softening area. One can assume that during the regeneration of an electrode (enlargement of an electrode working diameter by 20–25%), in accordance with the requirements of related standards, it is necessary to remove a softened layer of en electrode. The aforesaid activity is needed in order to restore the primary operating properties of an electrode (hardness). The number of conducted regenerations defines the total number of welds built up with a given electrode (until its complete wear).

The analysis of simulation results revealed that, both in case of 1 + 1 mm and 2 + 2 mm plates (Fig. 10), the bevel angle of an electrode has the greatest impact on welding temperature (and on the area of softening). This conclusion applies both to electrodes with an outer diameter of 20 mm and to electrodes with an outer diameter of 16 mm. Another factor affecting (to a lesser degree) the heating temperature of an electrode tip is the aforementioned outer diameter of an electrode. For the same values of a bevel angle, electrodes with outer diameters of 20 mm reveal lower heating temperature of working parts than electrodes with smaller outer diameters (16 mm). Similar observations could be made while assessing the size of the softening area of an electrode tip. It was also possible to observe that in case of hard welding parameters (heating to the highest temperatures), the lowest heating temperatures were characteristic of electrodes with a spherical working part. It should be remembered that electrode designs favouring lower heating temperatures contribute to smaller thicknesses of softening areas and prolong electrode life. Important data concerning proper electrode regeneration were obtained from simulation calculations related to the heating of an electrode tip located at different distances from the bottom of a cooling duct (5 mm and 3 mm). The temperature of an electrode tip does not change significantly with a decreasing distance from the surface of an electrode tip and is contained in the range 761–718 °C. Also the depth of a softening area does not change significantly (approx. 1.1 mm).

The diameter and also strength of a weld are strongly affected by an increase in an electrode working diameter caused by pressure at electrode operating temperatures.

In case of hard parameters, a 20% increase in the diameter of an electrode working area reduces the strength of a joint by 20% for 1 + 1 mm plates and by 14% for 2 + 2 mm plates.

In turn, in case of soft parameters, a 20% increase in the diameter of an electrode working area reduces the strength of a joint by 34% for 1 + 1 mm plates and by 50% for 2 + 2 mm plates.

In relation to soft parameters, the dependence of quality (weld nugget area) on an increase in the diameter of an electrode working area is not linear. In case of 1 + 1 mm plates, a further increase in the diameter of an electrode working area is accompanied by the complete absence of a weld nugget. The aforesaid phenomenon is a result of intensive cooling of a welding area by welding machine electrodes.

Verification of heating temperatures obtained through the comparison of simulated and calculated values confirms high compatibility of experiments and calculations. It is justified to assume that results obtained in simulations reflect actual relations in quick-changing processes present during the formation of a welded joint.

This article is part of greater research involving constant welding parameters such as the shape and dimensions of electrodes and variable welding parameters such as electrode force and/or travel. The remaining part of research (not described in this article) is concerned with force and travel of electrodes controlled using a servomechanical system. The tests performed and described in this publication are focused on the classical, i.e. pneumatic system controlling the force of electrodes.

The research will continue and involve tests focused on the effect of servomechanical electrode force modulation for the best welding conditions determined in the tests described in this article.

Appendix. Additional FEM calculations results

Temperatures (FEM) calculated (Fig. 11a and b) for the surface of electrodes with a 120° bevel angle and hard welding parameters are high and exceed 760 °C in the softening area 1.3 mm. In case of a bevel angle of 60°, temperature rises over 940 °C and the softening area increases to 2.4 mm. Fig. 11c and d presents heating temperatures of the aforesaid electrodes and the softening area for soft parameters.

The use of soft parameters for electrodes with bevel angles of 120° and 60° decreases the heating temperature of an electrode tip to 533 °C and 667 °C respectively. It was also possible to observe changes of the sizes of softening areas to 0.3 mm and 1.2 mm (Fig. 8). It should be noted, however, that obtained welds represent the quality level B, i.e. their nuggets have a diameter of 4 mm instead of 5 mm.

Fig. 11e,f and g,h presents simulation results for welding of 2 + 2 mm plates with the use of hard and soft parameters. Analyses concerned electrodes with outer diameters of 20 mm

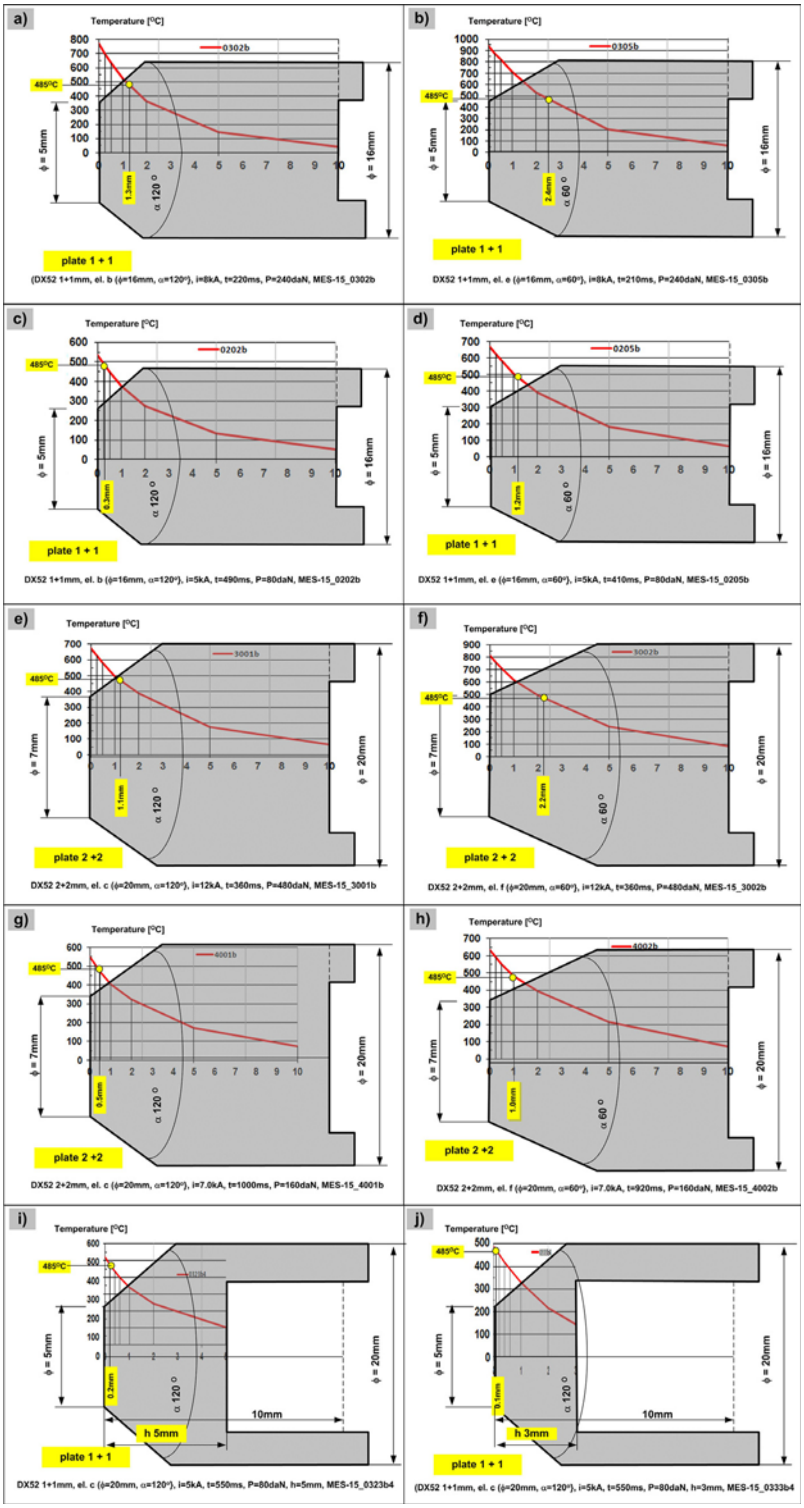


Fig. 11 – Temperature of heating of electrode tip with an outer diameter. (a, b) 16 mm and a bevel angle of (a) 120° and (b) 60° as well as the depth of softening areas during welding of 1 + 1 mm-thick plates with the use of hard parameters of welding. (c, d) 16 mm and a bevel angle of (a) 120° and (b) 60° as well as the depth of softening areas during welding of 1 + 1 mm-thick plates with the use of soft parameters of welding. (e, f) 20 mm and a bevel angle of (a) 120° and (b) 60° as well as the depth of softening areas during welding of 2 + 2 mm-thick plates with the use of hard parameters of welding. (g, h) 20 mm and a bevel angle of (a) 120° and (b) 60° as well as the depth of softening areas during welding of 2 + 2 mm-thick plates with the use of soft parameters of welding. (i, j) 20 mm and of electrodes for 5 mm- and 3 mm height of electrode tip. Thickness of plates: 1 + 1 mm, soft parameters of welding.

and 16 mm and bevel angles of 120° and 60°. The course of the heating temperature of electrodes during welding of 2 + 2 mm plates on an experimental stand is presented in Fig. 9.

Temperatures of heating of electrodes for 5 mm- and 3 mm height of electrode tip are presented in Fig. 11i and j.

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