Eugeniusz Turyk

Quality Criteria for G3Si1 and G4Si1 Electrode Wires

Abstract: The article presents test results concerning the quality of ISO 14341-A-G3Si1 and G4Si1 electrode wires based on electrode wire-related quality criteria in accordance with the requirements specified in the PN-EN ISO 14341 and PN-EN ISO 544 standards. The article discusses the critical defects of the wires (non-conformities with standard requirements) as well as defects not covered by the requirements of the standards, yet decisive as regards the assessment of electrode wires by the user.

Keywords: welding wire, MAG welding, G3Si1, G4Si1, defects of wires

DOI: *10.17729/ebis.2021.3/4*

Introduction

Industrial practice shows that the quality and properties of MAG welding electrode wires made by various producers may vary. Importantly, even electrode wires offered by the same manufacturer could differ in terms of their quality and properties in relation to individual batches. Such a situation raises a question concerning criteria governing the selection of electrode wires. Publication [1] states that the choice of a given electrode wire grade should not solely be based on its price but rather on welding-related and other technological properties affecting work efficiency, reliability, welding equipment service life as well as on aspects enabling the minimisation of costs related to the post-weld treatment of welds and near-weld areas.

This article aims to present test results and defects of ISO 14341-A-G3Si1 and G4Si1 electrode wires identified on the basis of requirements specified in the PN-EN ISO 14341 [2] and PN-EN ISO 544 standard [3]. The aforesaid defects constitute non-conformities with related standards as well as adversely affect the welding process and the quality of welded joints. The tests enabled the identification of the critical imperfections of wires, i.e. non-conformities with standard-related requirements, constituting the basis for complaints.

The wires subjected to the tests were coppered wires (Ø 1.2 mm) stored in the S 300 drums or B 300 rings. The wires were provided with inspection certificates 3.1 or conformity certificate 2.2 in accordance with PN-EN 10204.

Chemical composition of the wires

The chemical composition of most of the tested wires satisfied the requirements specified in the PN-EN ISO 14341 standard, Table 3A. Complaints connected with the porosity of welds were based on the chemical composition of the wires failing to meet the requirements of the above-named standard:

– wire EN ISO 14341-A-G 46 4 M21 3Si1 no. 61 failed to meet the requirements of the PN-EN

dr hab. inż. Eugeniusz Turyk – Łukasiewicz Research Network – Instytut Spawalnictwa, Research Group for Welding Technologies

ISO 14341 concerning the 3Si1 wire in relation to contents of manganese (0.46% instead of 1.3–1.6%) and silicon (0.03% instead of 0.7–1.0%),
– wire EN ISO 14341-A-G 46 4 M21 4Si1 no. 62 failed to meet the requirements of the PN-EN ISO 14341 concerning the 4Si1 wire in relation to contents of manganese (0.50% instead of 1.6–1.9%) and silicon (0.041% instead of 0.8–1.2%).

The complaint was justified by radiographic test results concerning welded joints made using the above-named wires (quality level NSD) as well as visual test results and fractographic test results concerning fillet welds (Fig. 1 and 2).

Tests of some electrode wires (being the subject of a complaint because of their porosity) revealed that their chemical composition satisfied the requirements of the PN-EN ISO 14341 standard and that the reason for weld porosity (quality level D or NSD) was the presence of impurities under the copper coating. The foregoing was confirmed by the difference between the total content of gases in wires no. 9, 11 and 18 provided with the copper coating and in the same wires without the surface layer (i.e. the copper coating) (Table 1).

Fig. 1. Surface porosity of the MAG butt weld made using the EN ISO 14341-A-G 46 4 M21 3Si1 wire no 61; quality level NSD

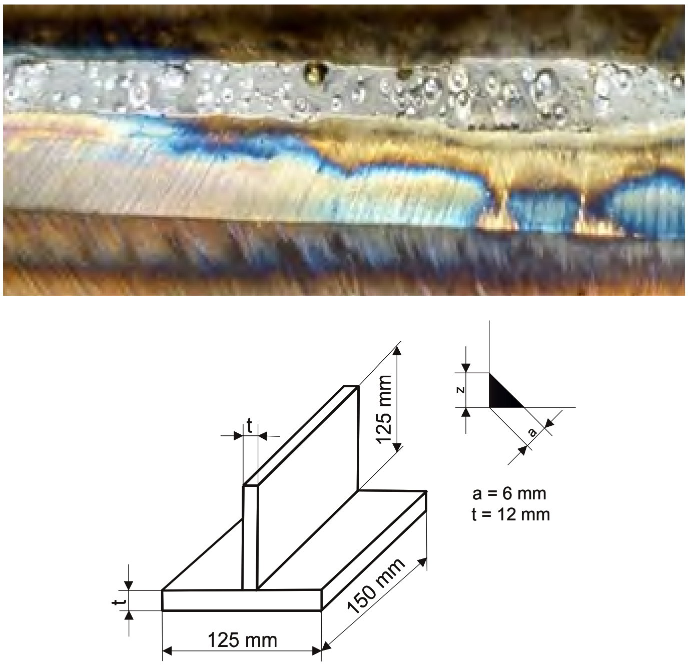


Fig. 2. Gas pores in the fracture of the MAG fillet weld made using the EN ISO 14341-A-G 46 4 M21 4Si1 wire no. 62 (a) and the sketch of a test joint (b)

The contents of gases in the wires were identified in relation to the as-received state (coated wire) and after the mechanical removal of the coating and impurities present under the coating (if any). The initial diameter of the wire amounted to 1.2 mm, whereas that of the wire without the coating was restricted within the range of 0.9 mm to 1.05 mm). The analysis included the application of the extraction method involving the melting of the specimen in a graphite crucible and the use of a TCHEN600 analyser (LECO) (to determine the contents of nitrogen, oxygen and hydrogen.)

The reduction of oxygen and hydrogen contents after the removal of the coating indicated the presence of organic impurities (technological lubricants) (Fig. 3) under the coating of the wire. For comparison, Table 1 presents results concerning the contents of gases in wire no. 2, representing quality level B (in terms of weld porosity). It should be noted that the PN-EN ISO 14341 standard does not specify requirements related to contents of gases in electrode wires.

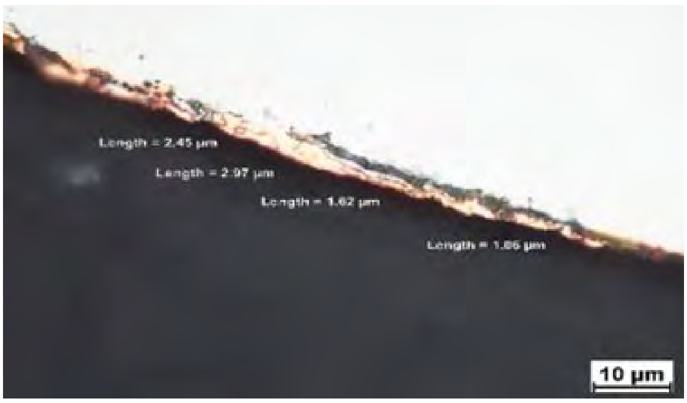


Fig. 3. Fragment of the cross-section of wire no. 3_04/20 – visible impurities under the copper coating; thickness of the copper coating restricted within the range of 1.06 µm to 2.97 µm

Table 1. Contents of gases in the ISO 14341-A-G3Si1 electrode wires [4]

Wire no.	Condition	N_2, ppm	O_2, ppm	H_2, ppm	S, ppm	ΔR, ppm
9	coppered	65	145	6.1	216.1	55.9
	without the surface layer	64	94	2.2	160.2	
11	coppered	157	137	3.0	297.0	14.7
	without the surface layer	157	123	2.3	282.3	
18	coppered	67	163	4.1	234.1	93.3
	without the surface layer	65	74	1.8	140.8	
2	coppered	58	84	3.2	145.2	13.1
	without the surface layer	57	73	2.1	132.1	

S – total content of nitrogen, oxygen and hydrogen in the wire,
ΔR – difference between the total content of gases in the wire with the coating and after its removal

In turn, islets of slag (welding imperfection) on the surface of the beads made using the MAG method (slag residue in accordance with PN-EN ISO 6520-1) are usually associated with the improper chemical composition of the electrode wire. Slag is composed of oxidation products formed as a result of metallurgical reactions taking place in the zone of welding arc and of the weld pool. According to publication [5], the products of such reaction "are partly removed as welding fumes, partly form slags, whose parts coagulate and come up to the surface forming slag islets and partly remain in the weld as non-metallic inclusions". According to publication [6], non-metallic inclusions are primarily composed of oxides: SiO_2–MnO–Al_2O_3. During the $CO_2 + O_2$ mixture-shielded welding process, the slag contained 29–32% SiO_2, 23–25% Fe_2O_3, 40–42% MnO and 3–4% Fe_{met}. [8]. The number and the size of slag islets depended not only on the chemical composition of the electrode wire but also on the welding process parameters and the composition of the shielding gas. The conclusion presented above was confirmed by results of surfacing tests involving the use of the ISO 14341-A-G4Si1 wire (φ 1.2 mm), welding current restricted within the range of 210 A to 220 A, arc voltage restricted within the range of 21 V to 23 V, a welding rate of 40 cm/min and a gas shielding of varied oxidation index I_0 (Fig. 4).

Fig. 4. Slag islets on the surface of the padding weld (side view) made using the following shielding gases: a) CO_2 (I_0 = 100) b) Ar + 25% CO_2 (I_0 = 25); c) Ar + 18% CO_2 (I_0 = 18); d) Ar + 2.5% CO_2 (I_0 = 2.5); e) Ar + 8% O_2 (I_0 = 4)

The test welding process performed using the ISO 14341-A-G4Si1 wire and a gas shielding having oxidation index I_0 ($I_0 = 1/2\ O_2 + CO_2$ [5, 8]) (within the range of 100 to 2.5) revealed that presence of slag in all of the padding welds. The highest amount of slag was observed in relation to the CO_2-shielded welding process (Fig. 4a), whereas the lowest amount of slag was formed when the welding process was shielded using the Ar+2.5%CO_2 mixture (Fig. 4d). However, a change of the shielding gas did not entirely prevent the formation of slag in the weld face. The formation of slags during welding was connected with the specific nature of metallurgical processes accompanying the MAG welding process [8] and did not indicate the improper chemical composition of the wires (i.e. inconsistent with the requirements of the PN-EN ISO 14341 standard).

Assessment of electrode wire quality based on the helical lift and the unwinding of the wire coil

In accordance with PN-EN ISO 544:2018-02, paragraph 7.2 "the lift and the condition of all wires should enable their steady and continuous feed by means of automated or partly mechanised welding machines". The helical lift is defined as the vertical lift between any part of the wire coil resting completely freely on the flat surface and the flat surface itself. In accordance with the above-named standard, in cases of wire reels, the diameters of which >200 mm, the helical lift should not exceed 50 mm.

The stiffness of the electrode wire is also connected with the so-called unwinding of the wire, i.e. the diameter of the wire coil resting freely on a flat surface and unwound manually from the reel. The size of unwinding is not standardised. Most manufacturers claim that a wire having a diameter of 1.2 mm, wound on a standard reel having a diameter of 300 mm, should unwind to a minimum diameter of 800 mm [1]. In turn, according to publication [5], "to ensure the good feedability of the electrode wire, its unwinding diameter should reach 1500 mm – in spite of the fact that AWS regulations only recommend a nominal diameter of 380 mm". According to publication [9], in relation to electrode wires, the diameter of which is restricted within the range of 1.2 mm to 2.0 mm, the wire unwinding diameter should be restricted within the range of 1000 mm to 1300 mm. Larger wire unwinding diameters (indicating the more plastic state of the wire) could result in the formation of wire contact gaps in the contact tube and, consequently, to welding process instability.

As regards one of the wires being the subject of the complaint (no. 6F) it was possible to observe a difference in the lift depending on the area, from which the wire was drawn. The test results concerning the helical lift of the aforesaid wire and its unwinding as well as those of the wire adopted as the model one (no. 7W) are presented in Table 2.

Table 2. Helical lift and diameters of coils of wires unwound from reels of wires nos. 6F and 7W

Specimen no.	Coil sampling area	Lift of wire no. 6F/ coil diameter	Lift of wire no. 7W/ coil diameter
1	Upper coils of a reel having a diameter of 300 mm (in the as-received state)	115 mm/φ 930 mm	0 mm/φ 790 mm
2		65 mm/φ 1030 mm	2 mm/φ 820 mm
3		55 mm/φ 990 mm	0 mm/φ 810 mm
4	Coils of a reel having a diameter of 220 mm (after using approximately half of the wire; wire layer thickness: 20 mm)	0 mm/φ 850 mm	0 mm/φ 800 mm
5		10 mm/φ 900 mm	0 mm/φ 920 mm
6		5 mm/φ 870 mm	0 mm/φ 900 mm
7		20 mm/φ 920 mm	0 mm/φ 860 mm

Fig. 5. Proper (a) and improper (b) shape of the support fillet weld

Unlike the coils wound on the reel having a diameter of 220 mm (satisfying related requirements), the upper coils of the reel of wire no. 6F (being the subject of the complaint) failed to meet the helical lift-related requirements of the PN-EN ISO 544 standard). The above-presented situation indicated the varied stiffness of the wire along its length (within one reel). In turn, wire no. 7W, drawn from the analogous areas of the reel, satisfied (in both cases) the requirements of the PN-EN ISO 544 standard.

The excessive lift is accompanied the "helical" unwinding of the wire, i.e. where the wire leaving the contact tube moves in various directions away from the contact tube axis. The aforesaid situation could lead to bead shape and dimension-related imperfections, incomplete fusion, incomplete root penetration etc. Figure 5b presents an example of the excessive asymmetry of the fillet weld (imperfection 512 in accordance with PN-EN ISO 6520-1) caused by the deviation of the wire tip from the contact tube axis during the MAG robotic welding of support elements.

The excessive stiffness of the wire may result in the non-uniform and stepped feed of the wire in the welding torch, making the welding process unstable. The electrode wire feed stability may also be disturbed by the non-uniform unwinding of the wire taking place both in relation to wires wound on the reel in a "coil-by-coil" manner (the so-called precise winding) and wires wound using a "slack" winding manner. During the tests, some of the precisely wound wires were also (sometimes) fed in a non-uniform (stepped) manner. For instance, wires nos. 62 and 63 unwound non-uniformly, with certain resistance. The reason was the improperly selected reel width, not taking into account the actual diameter of the wound wire, which ultimately adversely affected the winding process (Figures 6 and 7).

Assessment of the copper coating of electrode wires

The coating of the electrode wire in the as-received state was subjected to visual assessment based on the uniformity of the characteristic orange and red copper colour of individual wire coils. The tests [10] revealed that the electrode

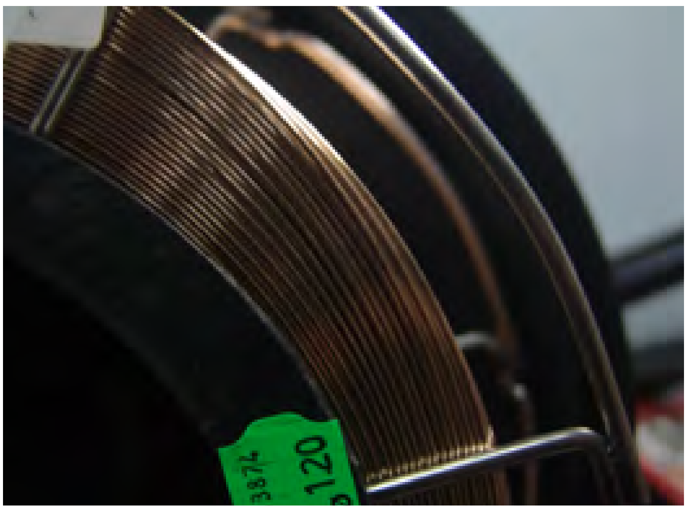


Fig. 6. Side view of the reel no. 62 with the wire unwound from the fourth layer from the top (arrows indicate the unwound coil)

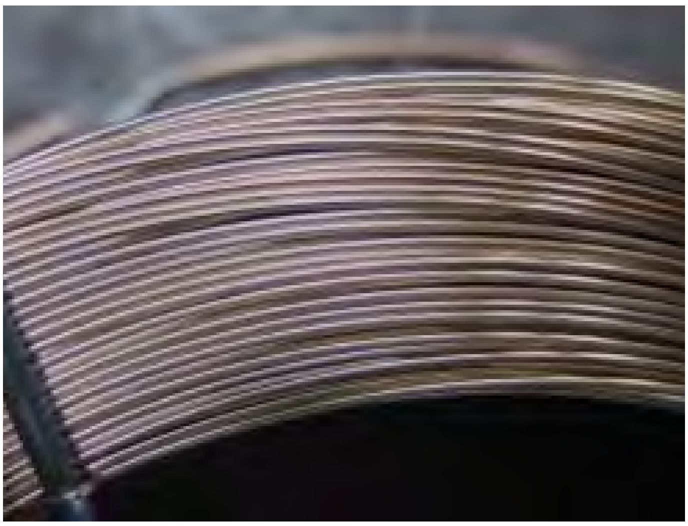


Fig. 7. Side view of the reel no. 63 revealing non-uniform winding

wires were characterised by various coating quality indicators:

- coating thickness restricted within the range of 0.01 μm to 0.49 μm,
- surface quality – ranging from the uniform surface of the coating to the surface containing cracks or even the partial tear of the wire material,
- coating adhesion – ranging from intense exfoliation to the entire lack of exfoliation,
- coating roughness restricted within the range of 8. to 10. of the roughness class (parameter Ra restricted within the range of 0.06 μm to 0.78 μm).

Similar to impurities located under the copper layer, partial tear, pitting and microcracks in the wire surface layer as well as its exfoliation are connected with the manufacturing technology [11]. The varying thickness of the coating, surface defects increasing the roughness of the wire surface (e.g. partial tear – see Fig. 8) and the exfoliation of the coating can increase friction resistance in the wire (spiral) duct of the welding torch and intensify the wear of copper contact tube openings in MAG welding torches. Apart from the statement that "the filler metal surface should be free from impurities and surface defects, which could adversely affect the welding process" (paragraph 7.2), the PN-EN ISO 544:2018-02 standard does not specify requirements related to the thickness and quality of the electrode wire coating.

Technological and welding-related properties of wires

Measurements concerning the coefficient of spatter-related losses (Ψ_r) of tens of ISO 14341-A-G3Si1 wires (having a dimeter of 1.2 mm) in relation to welding parameters (mechanised welding; a Kemppi pro 5000 semi-automatic welding machine) and welding current (restricted within the range of 100 A to 340 A) revealed that Ψ_r = 2.3–87% in relation to 56.6% of the wires (evaluated as good, example in Fig. 9), Ψ_r = 5.9–12.3% in relation to 37.7% of the wires (evaluated as satisfactory) and Ψ_r = 7.0–15.5% in relation to 5.7% of the wires (evaluated as unsatisfactory). The overlapping ranges of coefficient Ψ_r resulted from the scatter of spatter during the welding process performed using a specific electrode wire and a preset welding current range. According to users (welders), the welding process performed using wires from group Ψ_r = 7.0–15.5% proved unstable and the wires were the subject of a complaint. Excessive spatter is a wire-related defect, yet it is not mentioned in a standard.

The reason for one of the complaints, following the replacement of the ISO 14341-A-G3Si1 wire (φ 1.2 mm) (designated as no. 7W) with

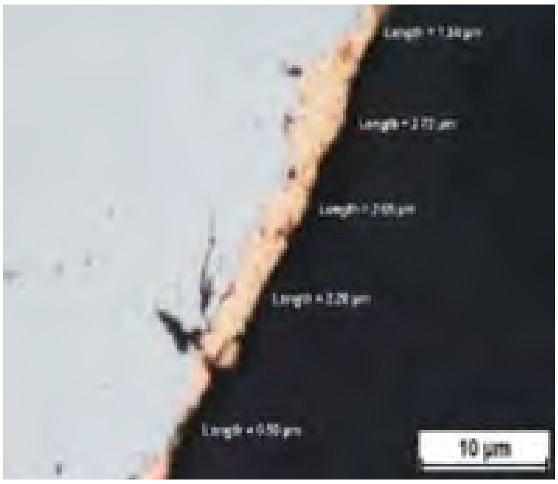


Fig. 8. Fragment of the cross-section of wire no. 3_03/20; varied thickness of the copper coating restricted within the range of 0.50 μm to 3.72 μm; visible crack (partial tear) in the wire material

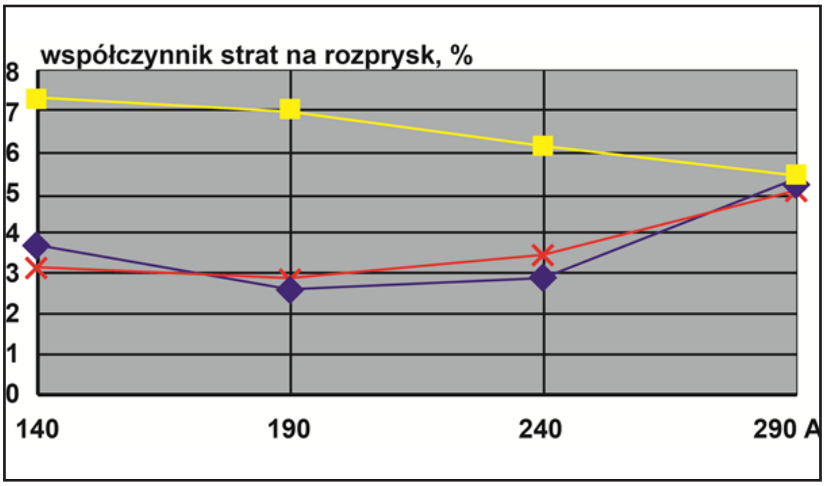


Fig. 9. Correlation between the coefficient of spatter-related losses and welding current: ♦ – wire no. 619, ▪ – wire no. 623, × – wire no. 604 (wire ISO 14341-A-G3Si1, shielding gas ISO 14175-M21-ArC-18)

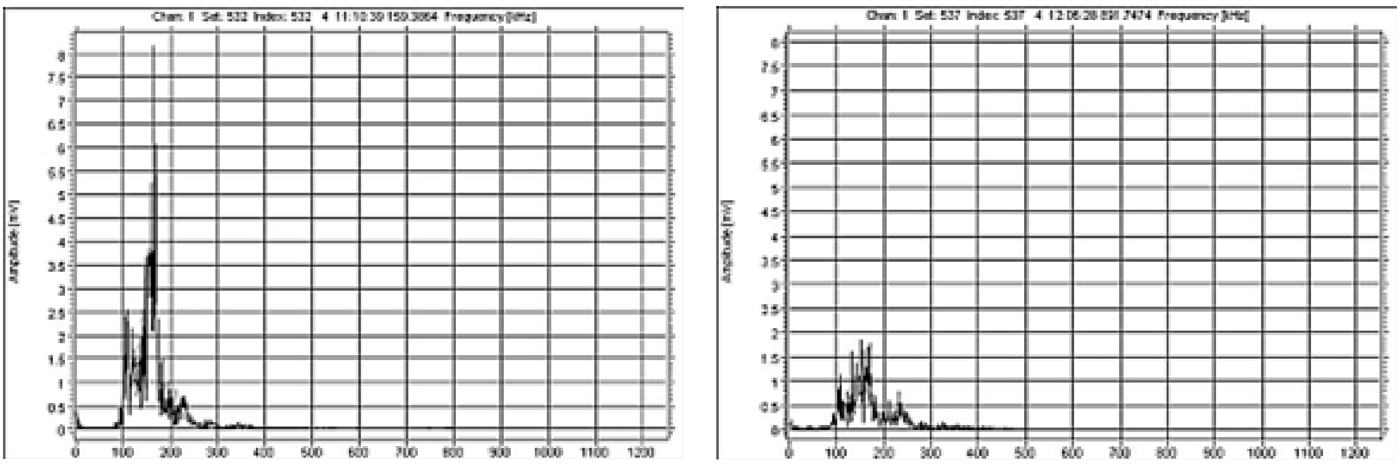
another electrode wire (designated as no. 6F) offered by a different manufacturer was, among other things, a welder's opinion stating that "the new wire is worse and noisier during welding and there is sometimes more spatter". The verification of the above-named statement involved the performance of comparative measurements of noise accompanying the gas-shielded (ISO 14175-M21-ArC-18) mechanised welding process using the above-named wires. The sound accompanying the surfacing process was recorded using an AMS3 device for testing acoustic emission (Vallen Systeme GmbH), i.e. a computer-aided system enabling the recording of sounds with the sensor attached directly to a plate/sheet subjected to surfacing. The analysis revealed that the noise level was higher during welding with wire no. 6F than during the process performed using wire no. 7W (Fig. 10). The foregoing indicated that the welding process involving the use of wire no. 7W was characterised by higher arc burning stability.

During the surfacing process, in addition to the recording of sounds, tests also involved the identification of welding current and arc voltage waveforms (using a PELS 03 microprocessor device (Table 3)). The subsequent comparison of the recorded waveforms revealed the lack of significant differences (between the waveforms) during short circuits. However, differences could be observed in relation to the maximum values of short circuit current in individual current waveforms, at moments when arc burning stability was disturbed. In relation to identical average values of welding current, the maximum values of short circuit current were higher as regards wire no. 6F than wire no. 7W. The foregoing explains the differences related to the size of spatter (Figures 11 and 12).

Table 3. Maximum values of short circuit current ($I_{short\ circuit}$ max.) during welding with wires no. 6F and no. 7W

Wire no.	**Current – average value, A**	**Arc voltage, V**	**Filler metal feed rate, m/min.**	**$I_{short\ circuit}$ max., A**
6F	120	19.0	2.7	225
	160	21.0	4.0	310
	200	22.5	6.1	330
	230	23.0	7.6	390
	280	27.0	10.0	540
7F	120	19.0	2.7	180
	160	21.0	4.0	250
	200	22.5	6.1	300
	230	23.0	7.6	300
	280	27.0	9.9	400

The verification of the opinion that "there is sometimes more spatter" involved measurements concerning the coefficient of spatter-related losses connected with the welding process performed using wire no. 6F and wire



Noise level during welding with wire no. 6F

Noise level during welding with wire no. 7W

Fig. 10. Comparison of noise level during welding with wires nos. 6F and 7W

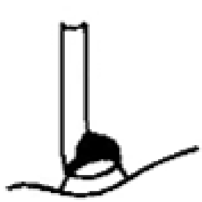


Fig. 11. Spatter resulting from the distribution of droplets following the rupture (explosion) of area reduction [12]

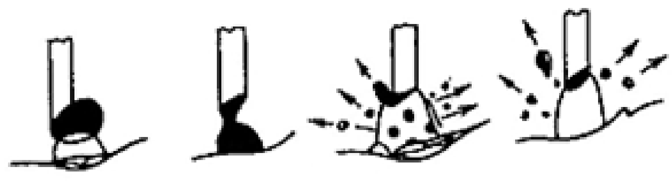


Fig. 12. Spatter resulting from the distribution of droplets from the wire in relation to higher short circuit current values [12]

no. 7W. The average value of the coefficient of spatter-related losses, identified on the basis of three measurements for a given welding current value, is presented in Figure 13.

The nature of the correlation between the coefficient of spatter-related losses and welding current restricted within the range of 140 A to 290 A was identical in relation to both wires. In relation to a current of 140 A and that of 190 A, wire no. 6F was characterised by the higher coefficient of spatter-related losses than wire no. 7W. In relation to a current of 240 A, the value of the coefficient was nearly the same. In turn, in relation to a current of 290 A, wire no. 6F was characterised by the higher coefficient of spatter-related losses than wire no. 7W.

Wire diameter

In accordance with the requirements of the PN-EN ISO 544 standard, acceptable deviations concerning a wire having a diameter of φ 1.2 mm are restricted within the range of +0.01 mm to -0.04 mm. Wire diameter-related tolerances affect the course of the welding process. Excessively large deviations from the wire diameter disturb the feed of the wire through the armouring of the flexible hose of the welding torch and the contact of the electric wire with the contact tube, potentially leading to arc burring instability.

The scale of marks applied during the measurements was the following: "2" - unsatisfactory (≥ +0.02 mm), "3" – satisfactory (-0.04 mm), "4" – good (-0.03 to -0.02 mm) and "5" – very good (-0.01 to +0,01). Among the wires subjected to the tests, only wire no. 24 failed to meet the diameter-related requirements (Table 4). It should be noted that the wire diameter is not an important parameter affecting the evaluation of the wire quality by users.

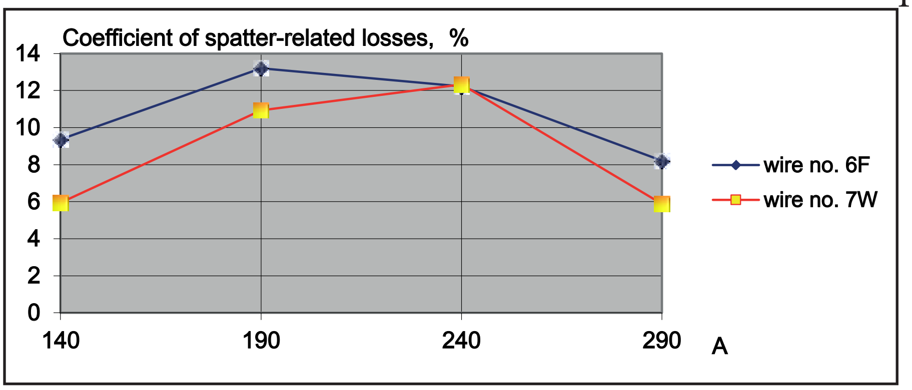


Fig. 13. Correlation between the coefficient of spatter-related losses and welding current during welding performed using wire no. 6F and no. 7W

Concluding remarks

1. Based on the wire quality-related criteria, specified in the requirements of the PN-EN ISO 14341 and PN-EN ISO 544 standards as well as on the basis of the related test results it could be stated that the critical defects (non-conformities with the standard requirements, constituting the basis for complaints) of the ISO 14341-A-G3Si1 and ISO 14341-A-G4Si1 electrode wires were the following:

Table 4. Marks concerning the diameters of selected wires

Wire no.	1	3	5	7	10	12	14	16	18	20	22	24	26	28	30	32	34	36
Mark	4	3	4	4	4	5	3	4	3	4	3	2	3	4	3	3	3	5

– chemical composition of the wire failing to meet the requirements of the PN-EN ISO 14341 standard,
– excessively high stiffness of the wire (i.e. a helical lift of more than 50 mm), failing to meet the requirements of the PN-EN ISO 544 standard,
– varied stiffness of the wire along its length (within one reel), with a lift failing to meet the requirements of the PN-EN ISO 544 standard,
– improper winding of the wire on the reel (responsible for the non-uniform feed of the electrode wire) failing to meet the requirements of the PN-EN ISO 544,
– surface defects of electrode wire coatings (adversely affecting the welding process) failing to meet the requirements of the PN-EN ISO 544:2018-02 standard (paragraph 7.2).

2. Wire defects not covered by the PN-EN ISO 14341 and PN-EN ISO 544 are the following:
– weld porosity caused by the presence of gases (coming from organic impurities (e.g. technological lubricants) located under the copper coating) in the welding area,
– excessive spatter,
– exfoliation of the copper coating inside the flexible of the MAG welding torch.

3. Both the critical defects and the above-presented defects not referred to in the requirements of the standards affect the evaluation of the wire quality by the user, the quality of welded joints and costs of the welding process.

References

[1] Alimow A.: Wybór drutu spawalniczego. Główne cechy drutu spawalniczego, które wpływają na jego jakość. Biuletyn Instytutu Spawalnictwa, 2019, no. 3.
[2] PN-EN ISO 14341:2011. Materiały dodatkowe do spawania – Druty elektrodowe i stopiwo do spawania łukowego elektrodą metalową w osłonie gazu stali niestopowych i drobnoziarnistych – Klasyfikacja.
[3] PN-EN ISO 544:2018-02. Materiały dodatkowe do spawania – Warunki techniczne dostawy spoiw i topników – Typ wyrobu, wymiary, tolerancje i znakowanie.
[4] Turyk E., Zeman M.: Wpływ czynników związanych z produkcją drutów elektrodowych na jakość połączeń spawanych metodą MAG. Materiały V Krajowej Konferencji Spawalniczej „Szczecin 2000", Międzyzdroje 2000.
[5] Pierożek B., Lassociński J.: Spawanie łukowe stali w osłonach gazowych, Wydawnictwa Naukowo-Techniczne, Warszawa 1987.
[6] Novozhilov N.M.: Osnovy metallurgii dugovoy svarki v aktivnykh zashchitnykh gazakh. Mashinostroyeniye, Moskva 1972.
[7] Asnis A.Ye., Gutman L.M.: Svarka v smesi aktivnykh gazov. Naukova dumka, Kiyev 1982.
[8] Węgrzyn J.: Fizyka i metalurgia spawania. Wyd. Politechnika Śląska, Gliwice 1990.
[9] Tekhnologicheskiye svoystva svarochnoy provoloki. Access date: 01.03.2019, http://www.spectechsoyuz.com/?id=21.
[10] Turyk E., Ruda A., Łomozik M.: Ocena powłok drutów litych do spawania metodą MAG. Biuletyn Instytutu Spawalnictwa, 2001, no. 4.
[11] Łuksza J., Skołyszewski A., Witek F., Zachariasz W.: Druty ze stali i stopów specjalnych. Wydawnictwa Naukowo-Techniczne, Warszawa 2006.
[12] Potap'yevskiy A.G.: Svarka v zashchitnykh gazakh plavyashchimsya elektrodom. Mashinostroyeniye, Moskva 1974.