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Welding Imperfections in Surfaced Layers

Abstract: The article presents the overview of various welding imperfections based on the classification of PN-EN ISO 6520-1:2009 and formed during surfacing. The article discusses specific surfacing-related imperfections and unclassified in the above-named standard as well as imperfections related to special requirements concerning surfaced layers.

Keywords: surfacing, welding imperfections of surfaced layers, classification, examples

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Introduction

The quality of a surfaced layer, the presence or the lack of variously originated welding imperfections or defects constituting unacceptable welding imperfections, significantly affect the functional properties of surfaced elements and their reliability as well as production and running costs. The analysis of various cases demonstrates that the greatest hazards as regards the service life of surfaced elements (products) are related to imperfections connected with metallurgical and thermal processes taking place during surfacing. In contract to welding, in surfacing the above-named processes are usually connected with the joining of dissimilar materials where the chemical composition and weldability of the surfaced layer and those of the base material may differ significantly.

Scientific reference publications discuss primarily welding imperfections in welded joints, the classification and reasons for the formation of imperfections when welding using various methods and materials, methods employed to prevent the formation of imperfections as well as tests of welded joints and the assessment of their quality. Significantly fewer publications are focused on welding imperfections formed during surfacing, and are primarily concerned with the effect of welding imperfections on the fatigue service life of surfaced elements.

Most imperfections of surfaced layers are also present in welded joints and for this reason they can be classified on the basis of standard PN-EN ISO 6520-1:2009 [1], according to which welding imperfections are divided into 6 groups, i.e. cracks (1), gas cavities (2), solid inclusions (3), incomplete fusions and lacks of penetration (4), shape and size-related imperfections (5) as well as various imperfections (6), i.e. not specified in groups 1÷5. Each imperfection is provided with a specific reference number. Overlay welds also contain specific

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imperfections connected only with the process of surfacing.

This publication aims to present various welding imperfections and imperfections of surfaced layers, both discussed in PN-EN ISO 6520-1:2009 and specific imperfections connected exclusively with surfacing and not classified in the above-named standard as well as imperfections related to special requirements.

Cracks in Surfaced Layers and Heat Affected Zones

Cracks are macro and microscopic discontinuities, usually having the form of a notch, caused by the local tearing of the surfaced layer or of the HAZ material. The acceptability of cracks in the surfaced layer depends primarily on the operating conditions of this layer in repair surfaced elements and/or elements surfaced preventively at the production stage. Cracks are imperfections where they may preclude operation from its very start or cause damage to an element, e.g. fracture, during its operation. Cracks are unacceptable in cut-off valves and fittings, hydraulic press plungers, metallurgical rolls, combustion engine valves etc. Examples of imperfections in the surfaced layer include a crack in the crater (104 according to PN-EN ISO 6520-1) of the surfaced layer of the sealing surface of a cut-off fittings element (Fig. 1), microcracks (1001 according to PN-EN ISO 6520-1) in the surfaced layer of cast iron elements formed through the use of an improper surfacing technology (Fig. 2), longitudinal cracks (1011 according to PN-EN ISO 6520-1) in the layer surfaced using a bad quality wire (Fig. 3) and as a result of improper surfacing parameters used in the process (Fig. 4). In some cases, cracks are accompanied by other welding imperfections such as gas cavities and incomplete fusions (Fig. 3 and 4) discussed below.

As regards the surfacing of steels characterised by higher hardenability, an improper

Fig. 1. Crack in the crater of the overlay weld of cut-off fitting element, made using the MIG method and a flux-cored wire (process 132) [2], filler metal of group Co2 according to PN-EN 14700 [3]

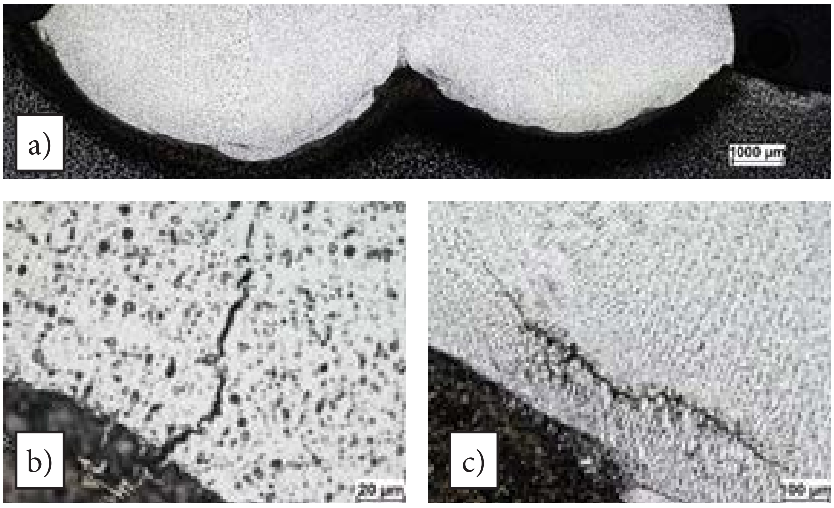

Fig. 2. Overlay weld made using the MAG method and a flux-cored wire (process 136, weld deposit ISO 1071 – T C NiFe-2 M) on an element made of grey cast iron: a) fragment of the overlay weld cross-section, mag. 50x; b) microstructure of the fusion zone with the microcrack, mag. 200x; c) microstructure of the fusion zone with the microcrack, mag. 500x.; electrolytic etching

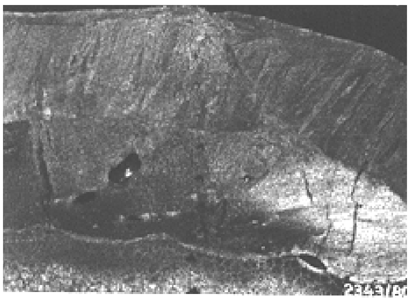

Fig. 3. Macrostructure of the 7 mm thick surfaced layer made using the MAG method (135) and a filler metal of group Fe1 – visible cracks and gas pores

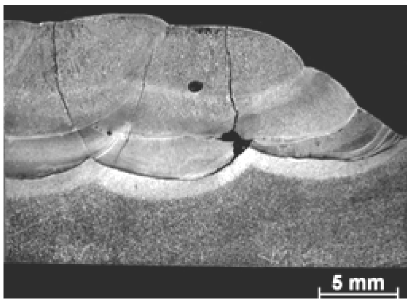

Fig. 4. Macrostructure of the three-layer overlay weld made using the MAG method (132) and a filler metal of group Co2. Cracks in the surfaced layer, incomplete fusion in layer 1 and a single gas pore between layer 2 and 3 [2]

Fig. 5. Partial tears (cracks) in the HAZ of the surfaced layer of a punch made of steel 41CrAlMo7

Fig. 6. Scaling of the surfaced layer of a punch made of steel 41CrAlMo7

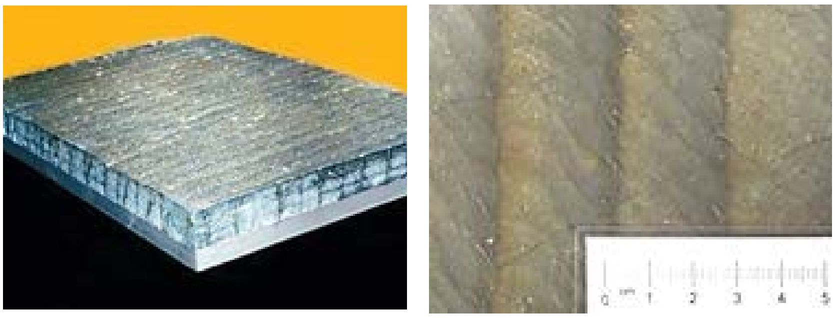

Fig. 7. Cracks in the work surface of abrasion-resisting plates hard surfaced using high-chromium cast iron of group Fe14 and a self-shielded flux-cored wire (process 114) [2]

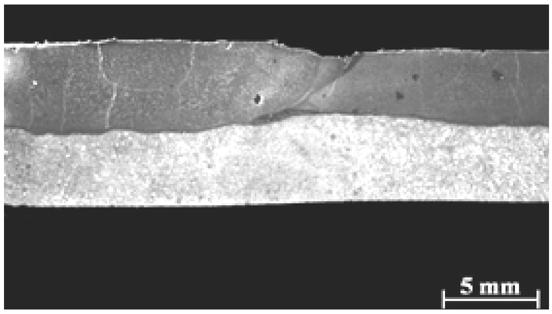

Fig. 8. Macrostructure of the high-chromium cast iron-surfaced layer – visible cracks and gas pores [2]

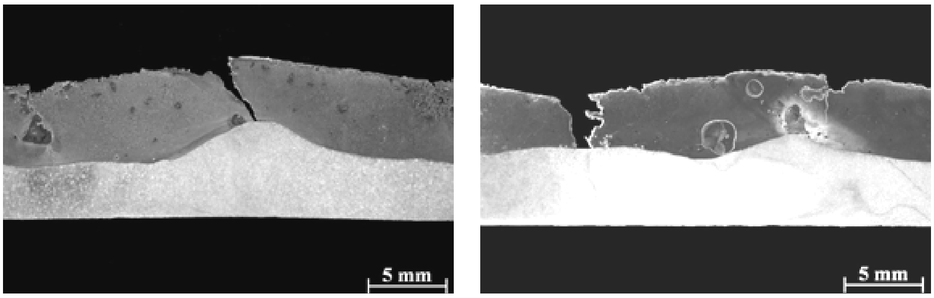

Fig. 9. "Open" cracks of the high-chromium cast iron-surfaced layer, reaching the base material [2]

Fig. 10. Torn-off fragment of the high-chromium cast iron-surfaced layer

surfacing technology may lead to the formation of cracks present in the HAZ which, in turn, may become tears (Fig. 5). Longitudinal cracks in the HAZ may trigger the scaling of surfaced layers (Fig. 6).

In cases of some element, the presence of cracks may not be of particular importance if they do not enter the base material or are not directed in parallel to the fusion surface and do not lead to the scaling of the surfaced layer. The above-named elements include pans and cones of closures of blast furnace charging devices, various types of chutes transporting minerals, storage bins and other structures requiring high abrasive wear resistance in metal-mineral friction conditions and erosion conditions. Such elements are hard surfaced using filler metals of group Fe13 ÷ Fe16 and Fe20 according to PN-EN 14700:2014-06 [2]. Exemplary cracks in the work surface of abrasion resisting plates are presented in Figure 7 and 8.

In some cases, cracks in the work surface made using high-chromium cast iron may lead to the unallowed scaling and tearing-off of an overlay weld fragment (Fig. 9-11).

Gas Cavities

Similar to welds, gas cavities in overlay welds are present in as [1]:

- gas cavities, i.e. cavities formed by gas confined in them (gas pores) and as surface pores i.e. gas pores breaking the surface of a run,
- contraction cavities, i.e. cavities caused by a contraction during solidification and (micro) shrinkage porosity, i.e. contraction cavities visible only under a microscope.

Gas cavities are responsible for the concentration of stresses and the reduction of fatigue service life of surfaced elements [5].

Gas pores in surfaced layers are mostly detected using radiographic tests. Figure 12 presents a radiogram of a 1.5 mm thick layer (after mechanical treatment of the surface) surfaced using the MIG method and solid wire EN 14640 - S Cu 5180 (CuSn6) onto a 5.5 mm thick steel plate – visible clusters of porosity (2013) also referred to as localised porosity.

Gas cavities are allowed in some cases, e.g. in the high-chromium cast iron-surfaced layer of plates operated in metal-mineral friction conditions (Fig. 13). In other cases, e.g. in overlay welds on critically important elements made of cast iron and exposed to pressure and metal-metal friction, porosity is unacceptable (Fig. 14 and 15).

The issue of porosity also accompanies the surfacing of elements made of nitrided steels, e.g. the screw of a plastic injection moulding machine made of steel 41CrAlMo7, surfaced using the TIG method (141) and rods made of steel 35HGSA without removing the nitrided layer (Fig. 16).

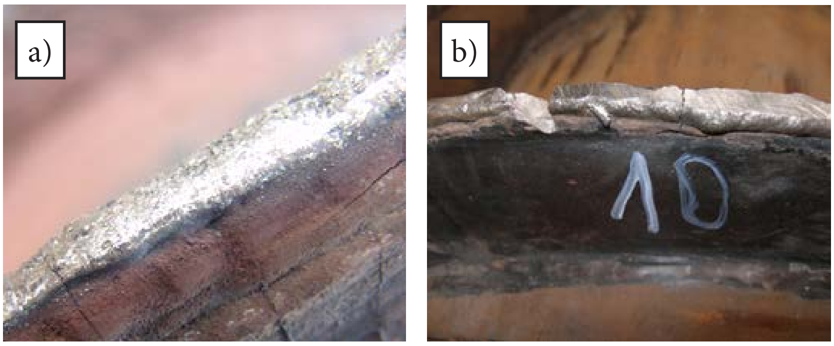

Fig. 11. Partly (a) and fully torn off (b) layer surfaced using self-shielded flux-cored wire (process 114), cast iron of group Fe15, on a screw coil (f 478 mm) of a screw conveyor

Fig. 12. Radiographic image of the single layer-surfaced specimen made using the MIG method (131) bronze CuSn6 – visible groups of gas pores having a diameter of ≤1 mm [4]

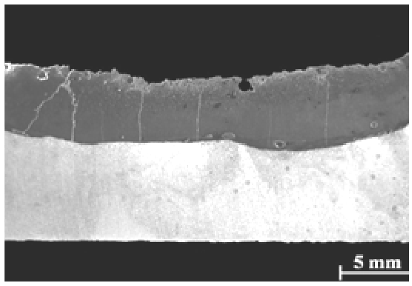

Fig. 13. Macrostructure of the high-chromium cast iron-surfaced layer (made using method 114) of abrasion-resisting plates – visible surface gas pore (2017 according to PN-EN ISO 6520-1) and cracks [2]

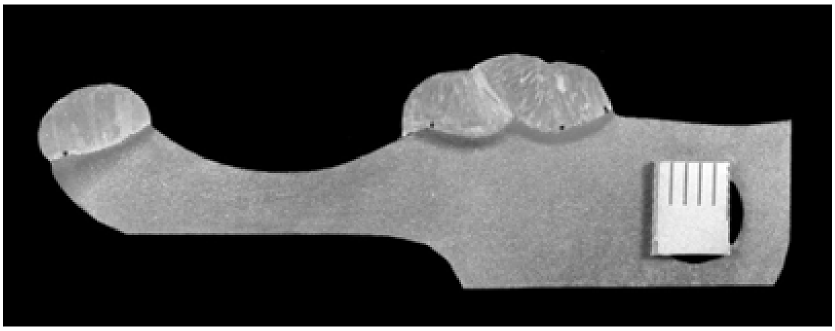

Fig. 14. Macrostructure of the overlay welds made using the MAG method (process 136, weld deposit classification ISO 1071 – T C NiFe-2 M) on an element made of grey cast iron – visible gas pores (2011 according to PN-EN ISO 6520-1) near the fusion line

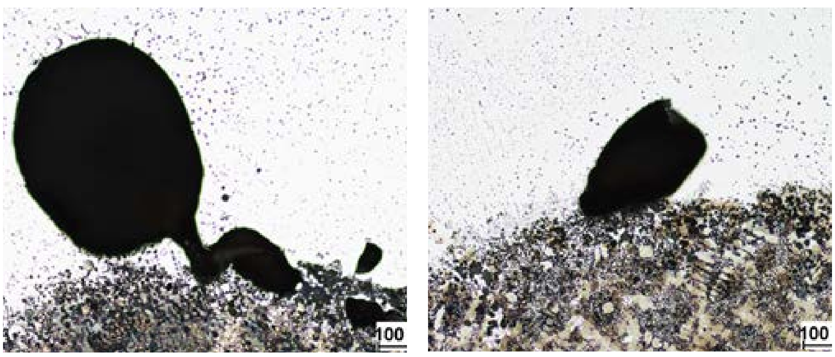

Fig. 15. Gas pores near the fusion line of the surfaced element (according to Fig. 14)

In addition to typical gas pores, the surfaced layer may also contain subsurface voids in the form of caverns. An exemplary cavern revealed during the mechanical treatment of the plasma-powder surfaced layer on an injection moulding machine screw coil made of steel 41CrAlMo7 is presented in Figure 17.

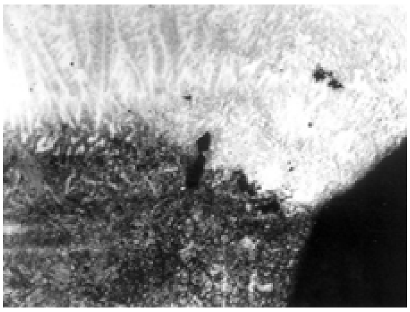

Fig. 16. Gas pores in the surfaced layer and in the fusion zone of the screw of a plastic injection moulding machine made of nitrided steel 41CrAlMo7

Fig. 17. Caverns in the plasma-powder surfaced layer (process 152) on a feeder screw coil and transverse crack

Solid Inclusions

Solid inclusions are foreign solids, of metallic or non-metallic origin, present in the surfaced metal. Solid inclusions are inclusions of slag (301 according to PN-EN ISO 6520-1), flux (302), oxides (303) as well as of metal particles (304), e.g. tungsten, copper etc. Slag inclusions are often formed, among other things, during MMA surfacing, MAG method-based flux-cored arc surfacing (process 136) involving the use of materials of group Fe6 and Fe8 (Fig. 18) and during submerged arc surfacing (Fig. 19).

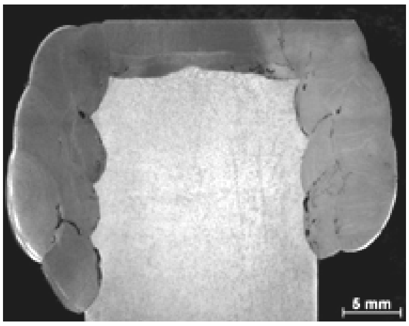

Fig. 18. Two-layer overlay weld with slag inclusions (3012) and gas pores between runs and layers [2]

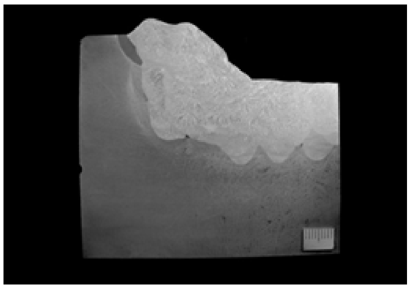

Fig. 19. Macrostructure of the submerged arc surfaced layer (process 121) of a crane wheel (ϕ 650 mm) made of cast steel L40GM – visible single slag inclusions

Incomplete Fusions

Incomplete fusions (400 according to PN-EN ISO 6520-1) represent the lack of connection between the surfaced metal and the base material, between successive runs in the surfaced layer (unclassified in PN-EN ISO 6520-1) or between successive layers (4012). Because of their (typically) flat shape, incomplete fusions are responsible for significant stress concentration thus reducing the fatigue service life of surfaced elements [5]. An exemplary lack of inter-run fusion formed during the MAG method-based mechanised girth surfacing (135) of the internal surface of a non-revolving tubular element is presented in Figure 20. During surfacing performed in the vertical down position (PG), the surfaced run metal runs onto and covers the previous not partially melted layer. The reason for the formation of the above-presented imperfection lies in an improper surfacing technology.

Fig. 20. Interlayer incomplete fusion (4012) during the MAG method-based surfacing (135) of the internal surface of the non-revolving tubular element (f170 mm), with visible voids in the form of slight gas pores

Incomplete fusions are typical of improper technological conditions of surfacing and are often formed, among other things, during plasma-powder surfacing involving the use of cobalt powders of group Co1-Co3 (Fig. 21) and in laser-powder surfacing processes (Fig. 22).

The surfacing of grooves may result in the irregularity having the form of the incomplete penetration of the root (imperfection 4021) of the last run; this imperfection is caused by the improper preparation of the groove and the improper arrangement of runs (Fig. 23).

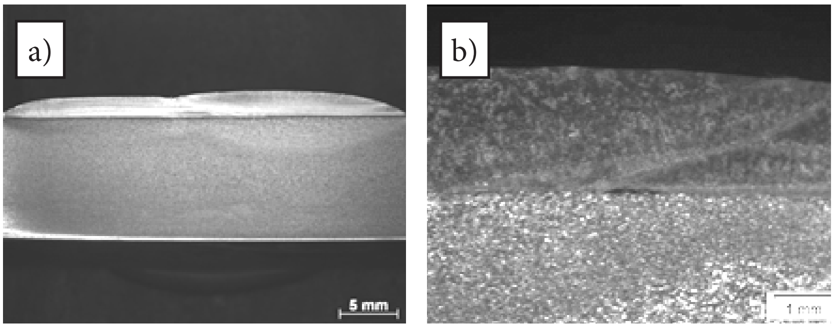

Fig. 21. Macrostructure of the overlay weld made using laser-powder surfacing (process 152) and cobalt powder [2]; alloy group Co1-Co3: a) main view, b) incomplete fusion (401 according to PN-EN ISO 6520-1)

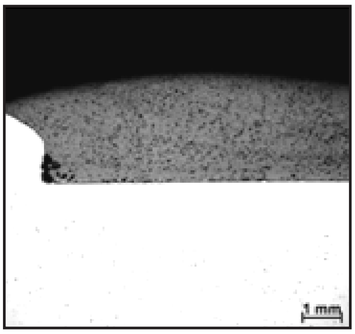

Fig. 22. Macrosection of the overlay weld made using laser-powder surfacing – incomplete fusion and gas pores [2]

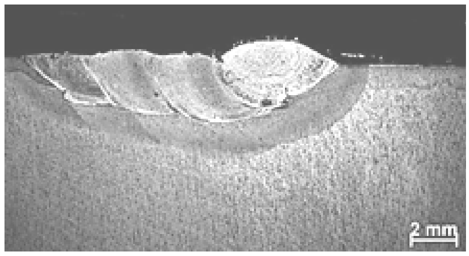

Fig. 23. Macrostructure of the overlay weld made using the TIG method (141), alloy group Fe1, in the groove – incomplete penetration of the root (imperfection 4021) of the last run and the gas pore (imperfection 2011) at the interface of the runs [2]

Shape and Size-Related Imperfections

Shape-related imperfection signifies the deviation of the shape or dimensions of the surfaced layer from agreed requirements:

- Irregular excess weld metal of the surfaced run along its length. This imperfection results from the instability of surfacing parameters, when surfacing is performed in restricted positions and is strongly related to the welder's skills.
- Insufficient overlapping of runs resulting from the instability of a surfacing process (e.g. the deviation of the electrode wire from the run axis) detected after the mechanical treatment of the surface subjected to surfacing.
- Irregular width of the surfaced run resulting from the instability of surfacing parameters, magnetic deflection (Fig. 24) or low welder's skills.

The presented imperfections, occurring regardless of a welding process and an alloy group, lead to the irregular thickness of the surfaced layer, improper final dimensions of the surfaced element after mechanical treatment (Fig. 25, 26) and, in some cases, to the irregular wear of surfaced elements, e.g. abrasion-resisting plates (Fig. 27).

Shape-related imperfections also include improperly restarted surfacing (517), i.e. a local unevenness formed as a result of improperly restarted surfacing (Fig. 27). The above-named

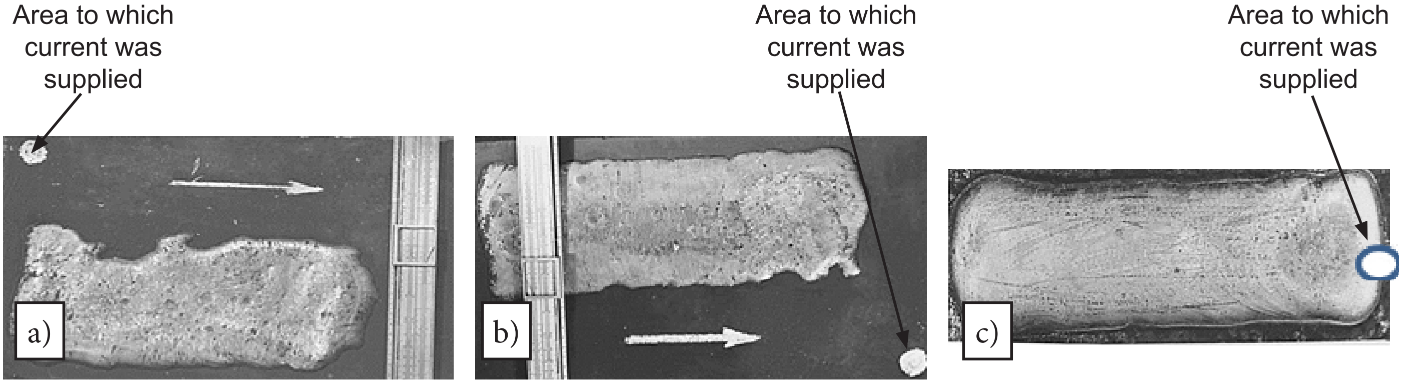

Fig. 24. Defective shape of the run surfaced using two 120 mm wide strips and the electroslag method depending on the current supply area and the effect of magnetic deflection: a – current supplied from the left side in relation to the run axis; b – current supplied from the right side in relation to the run axis; c – current supplied in the run axis

imperfection may lead to the formation of other welding imperfections deteriorating operational properties (e.g. incomplete fusions) of surfaced elements.

Various Imperfections

The group includes all welding imperfections which cannot be included in the above-presented groups, i.e.:

- stray arc during arc striking (601 according to PN-EN ISO 6520-1), striking mark – local damage to the surface of the base material adjacent to the overlay weld, caused by the accidental arc initiation. The acceptance of arc striking marks depends on the follow-up surface treatment and base material properties, particularly crack susceptibility.
- spatter (602 according to PN-EN ISO 6520-1) – drops of surfaced metal sprayed during surfacing and sticking to the surface of the base material or to the surfaced layer. The reasons for spatter include excessively high welding current, covered electrodes having eccentric cover, magnetic deflection etc. The acceptance of spatter on the surfaced layer depends on the operating conditions of a part subjected to surfacing.
- temper colours (610 according to PN-EN ISO 6520-1) – slightly oxidised surface formed e.g. on the clean surface of high-alloy steel exposed to a temperature restricted within the range of 290÷600°C and with access of air [6];
- slag residue (615 according to PN-EN ISO 6520-1) – insufficiently removed slag (remaining on the surface of the surfaced layer);

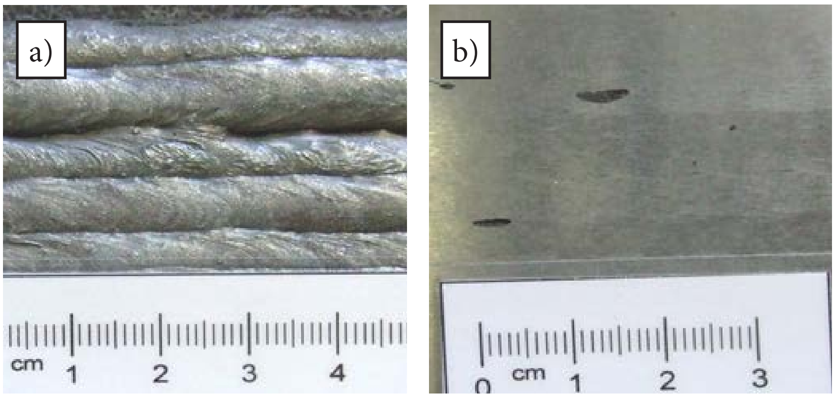

Fig. 25. Irregular excess weld metal of the multi-run surfaced layer: a) condition after surfacing, b) duct on the mechanically treated surface formed by the insufficient amount of the filler metal on the interface of the runs [2]

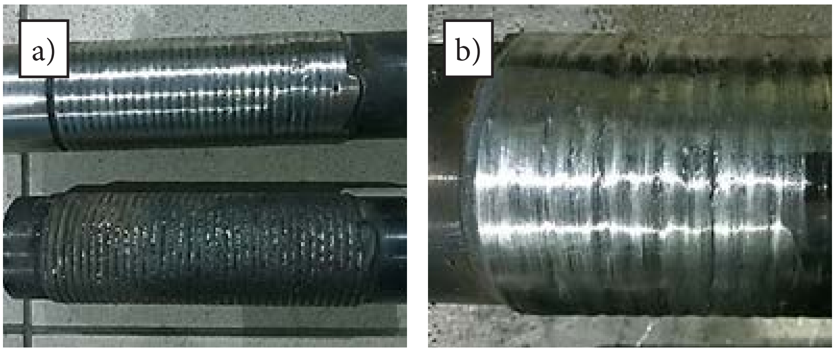

Fig. 26. Irregular excess weld metal of the corrosion-resistant MAG (135) method-surfaced layer on the shaft (ϕ 70 mm): a) main view of the shank after surfacing and mechanical treatment, b) fragment of the surfaced layer surface after turning to a required dimension

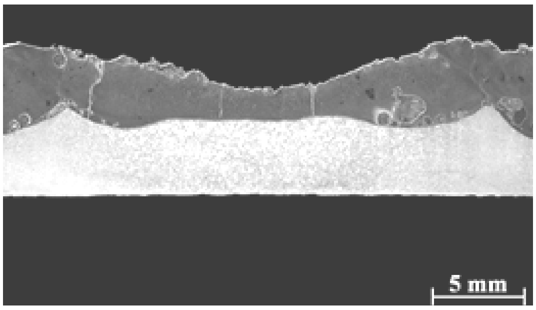

Fig. 27. Irregular wear caused by the irregular thickness of the high chromium cast iron-surfaced layer of the abrasion-resisting plate [2]

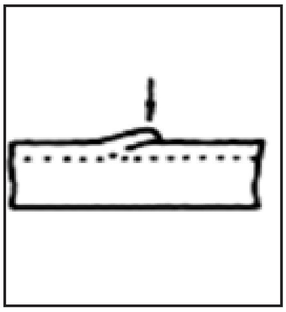

Fig. 28. Improperly restarted surfacing (517)

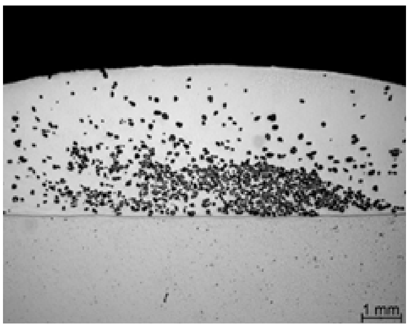

Fig. 29. Irregular distribution of W_2C particles on the Ni matrix in single-layer plasma surfacing [2]

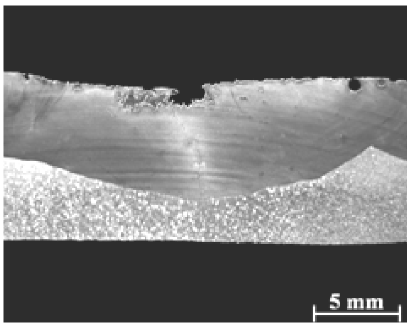

Fig. 30. Significant changes in the surfaced layer fusion depth (method 114, alloy groups Fe13 - Fe16) [2]

Table 1. Chemical composition of the overlay weld on the pipe made of steel 32HA using the ISO 14343-A - G 18 8Mn wire, MAG (135) method and shielding gas M21

Layer	Diameter, mm	Overlay weld thickness, mm	C, %	Si, %	Mn, %	Cr, %	Ni, %	Mo, %
1	300	2.0	0.229	0.520	3.549	10.36	4.514	0.024
	299	1.5	0.244	0.493	3.693	10.62	4.625	0.023
	298	1.0	0.252	0.542	3.652	10.35	4.599	0.024
	297	0.5	0.277	0.532	3.691	10.41	4.686	0.026
	296	0	0.266	0.534	3.732	10.33	4.846	0.027

Table 2. Chemical composition of the overlay weld on the pipe made of steel 32HA using the ISO 14343-A - G 18 8Mn wire, MAG (135) method and shielding gas M12

Layer	Diameter, mm	Overlay weld thickness, mm	C, %	Si, %	Mn, %	Cr, %	Ni, %	Mo, %
3	307	5.5	0.106	0.642	6.41	17.46	8.19	0.103
	305	4.5	0.102	0.644	6.45	17.46	8.36	0.103
2	303	3.5	0.125	0.624	5.86	15.77	7.56	0.090
	301	2.5	0.131	0.616	5.93	15.85	7.06	0.090
1	299	1.5	0.181	0.570	4.87	12.68	5.70	0.069
	298	1.0	0.185	0.617	4.58	12.24	5.25	0.043
	297	0.5	0.187	0.608	4.62	12.08	5.26	0.048
	296	0	0.181	0.656	4.56	12.07	5.34	0.047

Table 3. Chemical composition of the overlay weld on the shaft made of steel 41Cr4 using the ISO 14343-A - G 18 8Mn wire, MAG (135) method and shielding gas M21

Layer	Diameter, mm	Overlay weld thickness, mm	C, %	Si, %	Mn, %	Cr, %	Ni, %	Mo, %
1	74.0	2.0	0.257	0.538	4.308	11.84	5.402	0.034
	73.0	1.5	0.231	0.536	4.332	11.86	5.508	0.042
	72.0	1.0	0.236	0.516	4.273	11.58	5.409	0.036
	71.0	0.5	0.251	0.541	4.205	11.38	5.561	0.046
	70.0	0	0.252	0.499	4.098	11.14	5.310	0.036

Table 4. Chemical composition of the overlay weld on the shaft made of steel 41Cr4 using the ISO 14343-A - G 18 8Mn wire, MAG (135) method and shielding gas M12

Layer	Diameter, mm	Overlay weld thickness, mm	C, %	Si, %	Mn, %	Cr, %	Ni, %	Mo, %
3	81.0	5.5	0.129	0.778	6.784	17.60	7.582	0.072
2	77.0	3.5	0.130	0.726	6.259	16.87	7.224	0.067
	76.0	3.0	0.129	0.777	6.239	16.94	7.194	0.069
1	74.0	2.0	0.188	0.684	5.105	13.61	5.834	0.046
	73.0	1.5	0.190	0.682	5.103	13.56	5.765	0.046
	72.0	1.0	0.202	0.667	4.961	13.18	5.762	0.048
	71.0	0.5	0.211	0.681	4.922	13.07	5.739	0.050
	70.0	0	0.196	0.681	5.125	13.40	5.624	0.052

- irregular distribution of hard particles (carbide grains) in the nickel matrix (in the cross-section of the surfaced layer) leading to the irregular wear of this layer (Fig. 29);
- significantly varied degree of the stirring of the overlay weld with the base material, because of which the metallurgical objective connected with the chemical composition of the surfaced layer is not satisfied (Fig. 30).

Imperfections in Relation to Special Requirements

In some cases, surfaced layers must satisfy special requirements imposed by detailed regulations or by the customer. Exemplary special requirements are the following:

- requirements concerning the chemical composition of nickel-surfaced layers (having a specified thickness) of walls of gas-tight waste incineration boilers: the content of iron determined on the overlay weld surface should not exceed 6% in relation to overlay welds made automatically and 10% as regards overlay welds made manually [7];
- requirements concerning the minimum qualified thickness of a hard surfaced layer (test thickness according to item 7.4.3 of PN-EN ISO 15614-7:2009 [8]);
- requirements concerning the minimum qualified thickness of a corrosion-resistant layer (chemical composition specified according to item 7.4.3 of PN-EN ISO 15614-7:2009).

An exemplary welding imperfection related to special requirements is demonstrated by the surfacing of a pipe (ϕ 296x28 mm) made of steel 32HA and a shaft (ϕ 70 mm) made of steel 41Cr4 with a corrosion-resistant layer. Because of the fact that iron alloys containing more than 12% Cr undergo passivation easily and are resistant to corrosion, particularly in oxidising environment [9], a criterion adopted when surfacing a corrosion-resistant layer on the above-named element was the content of chromium amounting to a minimum of 12% in a single-layer overlay weld. In addition, it was assumed that surfacing should be performed using the MAG (135) method, the ISO 14343-A - G 18 8Mn wire (typical chemical composition of the weld metal: 0.08% C, 19% Cr, 9% Ni and 7% Mn) and the M21 shielding gas mixture (Ar + 18% CO_2). The check analysis of the chemical composition revealed that as regards the surfacing of the pipe (ϕ 296×28 mm) made of steel 32HA the chromium content amounted to 10.33% in the fusion line and did not exceed 10.62% in the first layer (Table 1); the chromium content-related requirement was not satisfied. To eliminate the above-named imperfection and satisfy the criterion of ≥12% Cr, another shielding gas, i.e. M12 (Ar + 2.5% O_2) was applied without changing surfacing parameters. The content of chromium obtained in the fusion line amounted to between 12.07% and 12.68% with the thickness of the first layer being 1.5 mm. In the second surfaced layer the content of chromium increased to 15.85% and reached up to 17.46% in the third layer.

When performing the M21 gas-shielded surfacing of the shaft (ϕ 70 mm) made of steel 41Cr4, the content of chromium in the fusion line amounted to 11.14% and did not exceed 11.84% where the thickness of the first layer amounted to 2.0 mm (Table 3). After using the M12 shielding gas mixture, the content of chromium in the fusion line amounted to 13.40% and to 13.61% in the first layer having a thickness of 2.0 mm. In the second surfaced layer the content of chromium increased to 16.94% and reached 17.60% in the third layer.

Surfaced Layer Quality Assessment

The quality of surfaced layers represents the level of their features and properties required by the user and previously agreed with the designer and the manufacturer. The quality level does not characterise the entire product but is limited to the overlay weld and HAZ.

In cases of stable and properly developed technological processes of surfacing, the appearance of welding imperfections could be regarded as random events, to which specific distributions apply (e.g. Poisson distribution in relation to the number of imperfections) and the level of which should be assessed on the above-named basis. However, the quality of surfaced layers is usually assessed using a zero-one approach where zero stands for the failure to meet related requirements and one represents their satisfaction. Unlike in welding, where the PN-EN ISO 5817:2014-05 [10] specifies three quality levels of welded joints designated as B (strict requirements), C (medium requirements) and D (mild requirements) with detailed boundary dimensions, surfacing is not governed by any such regulation.

The selection of criteria concerning the size of allowed welding imperfections should be at the discretion of the designer and depend on the type of a surfaced element as well as on types of loads, i.e. static, variable or, additionally, dynamic. Other aspects of crucial importance include operating conditions, required operating properties of surfaced layers and consequences of failures, if any.

An innovative destructive testing-based methodology concerned with assessing the quality of surfaced layers on the basis of internal welding imperfections was proposed in publication [11]. The adopted assessment criterion was the proportion of the area of welding imperfections on the macroscopic metallographic specimen along the weld axis, over a distance of 50 mm, to the area of the overlay weld on the metallographic specimen, so-called parameter "a". Assessment criteria concerning the quality of overlay welds in relation to parameter "a" were formulated by analogy to the quality levels of welding imperfections, i.e. quality level NB ($a \leq 0.20\%$), level NC ($0.20\% < a \leq 0.40\%$) and level ND ($0.40\% < a \leq 0.60\%$).

Summary

The overview of various welding imperfections of surfaced layers confirmed the possibility of classifying most of the imperfections in accordance with PN-EN ISO 6520-1:2009, yet also revealed the existence of specific surfacing-related imperfections not classified in the above-named standard as well as imperfections with special requirements. Specific surfacing-related imperfections not classified in PN-EN ISO 6520-1:2009 include the following:
- scaling of the surfaced layer (see Fig. 6), a torn-off fragment of the surfaced layer (Fig. 10);
- cavern (Fig. 17);
- shape-related imperfections characteristic of surfaced layers such as the irregularity of the excess weld metal of the multi-run surfaced layer (Fig. 25, 26) or the irregular thickness of the surfaced layer (Fig. 27);
- irregular distribution of solid particles in the surfaced layer matrix (Fig. 30);
- irregular stirring of the overlay weld with the base material (Fig. 31);
- insufficient thickness of the overlay weld failing to meet the requirements concerning the minimum qualified thickness of the surfaced layer;
- overlay weld chemical composition inconsistent with related requirements (Table 1, 3).

As can be seen, it is advisable that the classification of welding imperfections according to EN ISO 6520-1 be extended to include surfacing imperfections or a separate classification of such imperfections be introduced.

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