Investigations

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Methodology of Assessing the Quality of Surfaced Layers on the Basis of Internal Welding Imperfections

Abstract: In manufactured or refurbished machinery parts, surfaced layers are often characterised by the presence of welding imperfections, usually reducing the active life of equipment and machinery. The development of an appropriate methodology and the specification of assessment criteria concerning the quality of surfaced layers could facilitate the assessment of surfaced elements in relation to their load transferring capability. The article describes tests involving specimens surfaced using various methods, proposes a methodology of testing the quality of overlay welds on the basis of macroscopic observations and specifies criteria to be applied when assessing the above named quality on the basis of established dependences.

Keywords: non destructive testing, welding imperfections, quality assessment

DOI: *10.17729/ebis.2016.3/1*

Introduction

Surfacing is a welding process providing work surfaces of products, e.g. machinery parts, with various special properties. Surfacing is used both when manufacturing and refurbishing elements, where the weight of metal being surfaced usually constitutes no more than several per cent of the general weight of elements being subjected to surfacing [1]. As a result, it is possible to reduce the wear and tear of expensive materials. In addition, repeated refurbishment reduces metal losses as regards the preparation of spare parts [1, 2, 3].

In manufactured or refurbished parts of machinery, vehicles and other products, surfaced layers are frequently characterised by the presence of welding imperfections such as gas pores, inclusions of slag, flux or oxides, incomplete fusions etc., significantly reducing the active life of elements [4, 5, 6, 7]. Each imperfection triggers the accumulation of stresses, potentially constituting the area of damage, precluding the use of a given product. The development of an appropriate methodology and the specification of assessment criteria concerning the quality of surfaced layers could facilitate the assessment of surfaced elements in relation to their load transferring capability. In order to reach this target, it was necessary to test rollers made of steel C45, subjected to manual metal arc surfacing (process 111) and MAG surfacing with solid wire electrode (process 135) [7],

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using various thicknesses of surfaced layers.

Test Materials

Base materials used in the tests were rods made of steel C45. The chemical composition of the above named steel is presented in Table 1, whereas its mechanical properties are presented in Table 2.

Table 1. Chemical composition of steel C45 according to check analysis

Chemical composition							
C	Mn	Si	P	S	Cr	Ni	Mo
0.45	0.57	0.27	0.024	0.028	0.19	0.07	0.08

Table 2. Mechanical properties of steel C45

Re, MPa	Rm, MPa	A_5, %	Z, %	Remarks
441,1÷464,9	637,3÷657,3	25,2÷26,2	45,0÷51,0	Material in the normalised state
The tests of mechanical properties were performed using specimens having a diameter of 10 mm, in accordance with the requirements of standard PN-EN ISO 6892-1				

Tables 1 and 2 reveal that both the chemical composition and the mechanical properties of steel C45 satisfy the requirements of PN-EN 10083-2. The rollers were surfaced using process 111 and covered electrodes EB 150 (ISO 2560-A:E 42 4 B 4 2) having a diameter of 3.25 mm. Surfacing performed using process 135 involved the use of wire SpG4S (ISO 14341-A-G 4Si1) having a diameter of 1.2 mm. Both electrodes EB 150 and wire SpG4S enable the obtainment of weld deposit having a yield point similar to the yield point of steel C45. The MAG welding process was shielded by a typical mixture, i.e. containing 80% of argon and 20% of carbon dioxide (ISO 14175-M21-ArC-20).

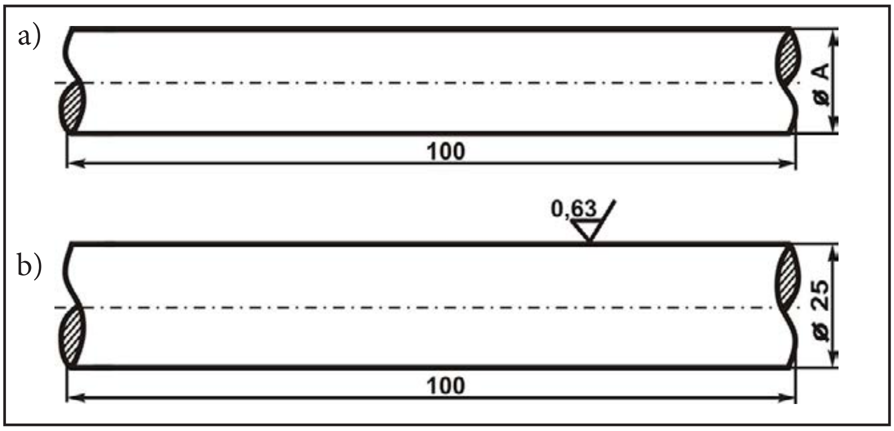

Fig.1. Shapes and dimensions of the test specimens: a) prepared for surfacing: A=23 mm – for the specimens with the surfaced layer having the thickness of *g*=1 mm, *A*=21 mm – for the specimens with the surfaced layer having the thickness of *g*=2 mm; b) after surfacing and mechanical treatment

Shape, Dimension and Preparation of Specimens

Figure 1 presents the specimens (along with their shape and dimensions before and after surfacing) used in the tests.

As can be seen in Figure 1, after surfacing and mechanical treatment, the working diameters of the specimens amounted to 25 mm, whereas the thickness of surfaced layers amounted to g=1 mm and g=2 mm respectively. The specimens were surfaced alternately along their longitudinal axes.

During surfacing performed using process 111, surfacing current (I) amounted to 120 A. The parameters used when surfacing performed using process 135 were the following: I=110 A, U_l=20 V, v_{el}=2.6 m/min and a shielding gas flow rate of 12 l/min.

The surfaced specimens were subjected to normalising at a temperature 850-870°C and to cooling in air. As steel C45 is also used for toughening (hardening and tempering) entailing the risk of crack formation, the tests also involved the preparation of toughened specimens. The parameters of toughening were the following: hardening from a temperature of 820-860°C in water and high tempering at a temperature of 600-660°C. The types of the specimens used in the tests are presented in Table 3.

Tests of the Specimens

After mechanical and heat treatment, the surfaced specimens were subjected to visual,

Table 3. List of test specimens

No.	Types of speciment	Thickness of surfaced layer	Type of heat treatment
1 2	Surfacing performed using process 111	1 mm 2 mm	Normalising
3 4	Surfacing performed using process 135	1 mm 2 mm	
5 6	Surfacing performed using process 111	1 mm 2 mm	Toughening
7 8	Surfacing performed using process 135	1 mm 2 mm	

Note: For each version, 5 specimens were made.

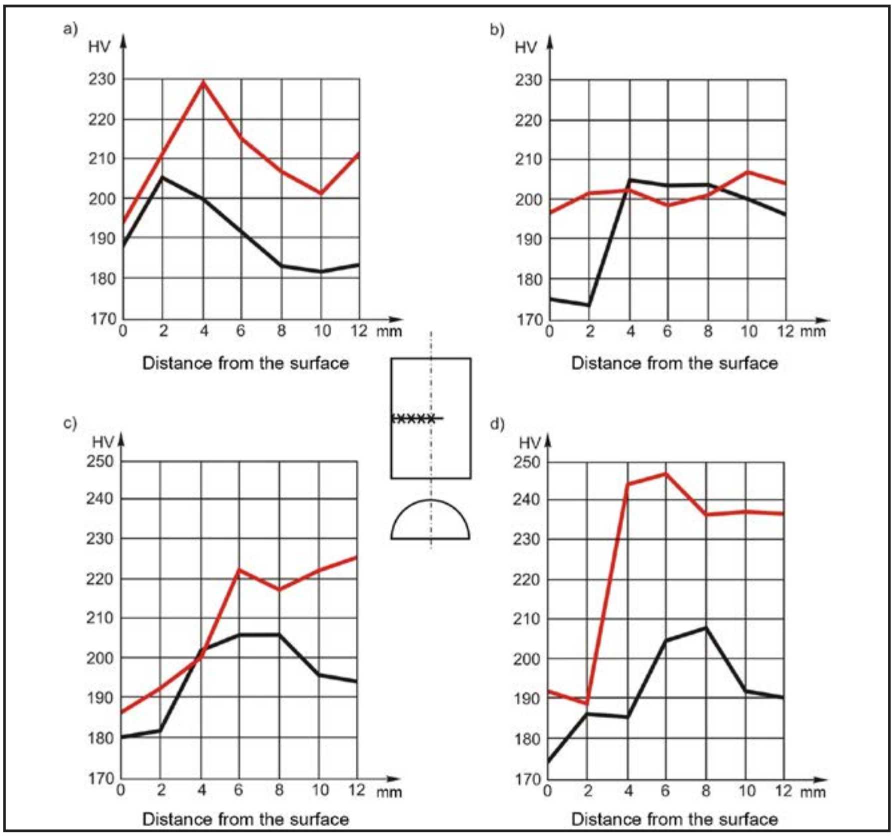

Fig. 2. Hardness distribution in the specimens subjected to normalising (—) and toughening (—): a) surfaced using process 111 and the surfaced layer thickness of g=1mm; b) surfaced using process 111 and the surfaced layer thickness of g=2 mm; c) surfaced using process 135 and the surfaced layer thickness of g=1 mm; d) surfaced using process 135 and the surfaced layer thickness of g=2 mm

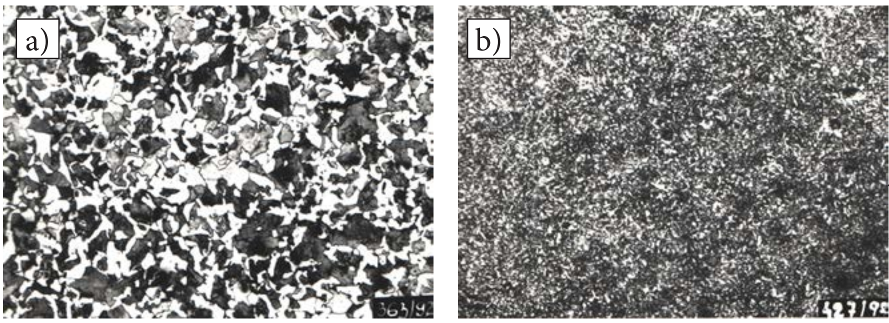

Fig. 3. Structure of steel C45: a) after normalising – pearlite + ferrite; etchant: Nital; 250x magnified; b) after toughening – highly toughened martensite (sorbite), etchant: Nital; 250x magnified;

penetrant and magnetic particle tests.

The visual tests did not reveal the presence of cracks on the tested surfaces. In some cases, single gas pores having a diameter of less than 1 mm and a depth of approximately 0.5 mm were observed.

The penetrant tests and magnetic particle tests did not reveal the presence of linear indications on the tested surfaces. However, numerous non-linear indications were observed. Both the penetrant and magnetic particle tests confirmed the results obtained in the visual tests of the rollers.

In order to verify the correctness of the heat treatment, the surfaced rollers were sampled for elements (cut in the plane passing through their longitudinal axis) used in Vickers hardness measurements. The hardness measurements were performed maintaining 2 millimetre intervals (from the surface of the element to its longitudinal axis). In the above named manner, the cross-sectional hardness distribution of the specimen was obtained. The hardness measurement results are presented in Figure 2. Figure 2 reveals that the specimens subjected to toughening were characterised by higher hardness that the hardness of the specimens subjected to normalising. The measurement results confirm the correctness of heat treatment affecting the test specimens.

The structures of the base material after heat treatment and the structures of the individual zones of the surfaced specimens were determined on the basis of microscopic tests. Selected structures are presented in Figures 3-7. Presented structures are as expected, which additionally confirms the correctness of the post-weld heat treatment.

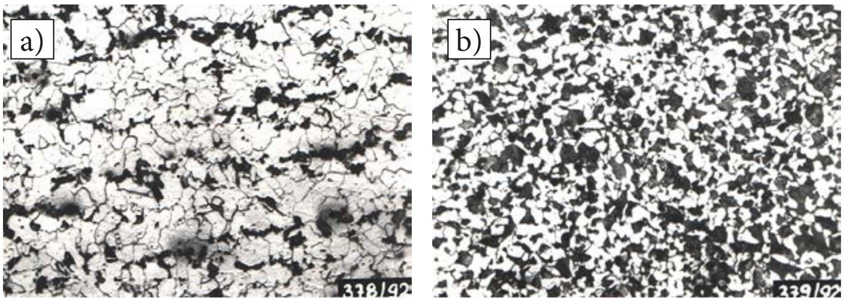

Fig. 4. Structure of the overlay weld (*g*=1 mm) and the heat affected zone (HAZ) of the specimen surfaced using process 111 and subjected to normalising: a) overlay weld structure – ferrite + pearlite, etchant: Nital; 250x magnified; b) HAZ structure – pearlite + ferrite, etchant: Nital; 250x magnified

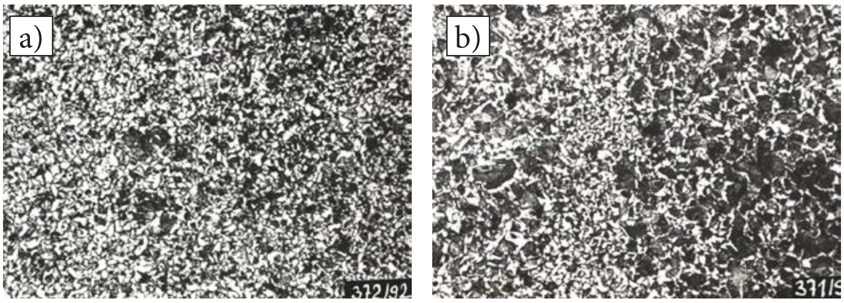

Fig. 5. Structure of the overlay weld (*g*=1 mm) and of the HAZ of the specimen surfaced using process 111 and subjected to toughening: a) structure of the overlay weld – pearlite + ferrite, etchant: Nital; 250x magnified; b) structure of the HAZ – pearlite + ferrite, etchant: Nital; 250x magnified

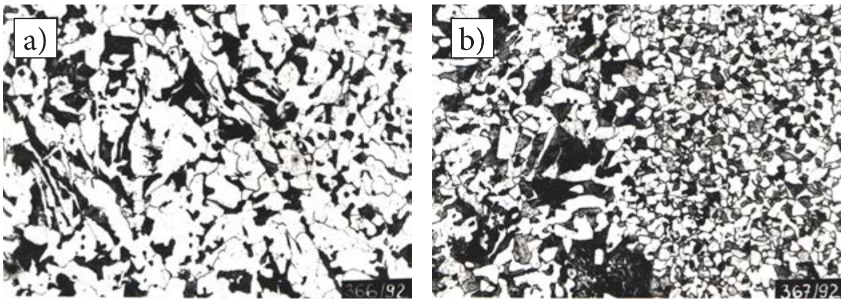

Fig. 6. Structure of the overlay weld (*g*=2 mm) and of the HAZ of the specimen surfaced using process 135 and subjected to normalising: a) structure of the overlay weld – ferrite + pearlite, etchant: Nital; 250x magnified; b) structure of the HAZ – ferrite + pearlite, etchant: Nital; 250x magnified

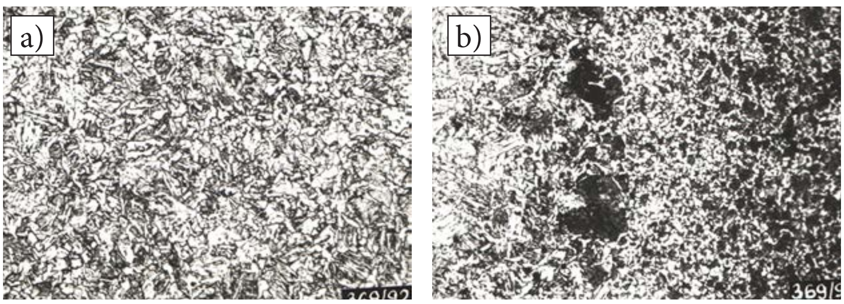

Fig. 7. Structure of the overlay weld (*g*=2 mm) and of the HAZ of the specimen surfaced using process 135 and subjected to toughening: a) structure of the overlay weld – ferrite + pseudo pearlite + traces of bainite, etchant: Nital; 250x magnified b) structure of the HAZ – ferrite + pseudo pearlite + traces of bainite, etchant: Nital; 250x magnified

Quality of Welds

In order to assess the quality of welds on the basis of internal welding imperfections, the test specimens were sampled for elements used to prepare metallographic specimens (Fig. 8).

The plane of each of the metallographic specimens was situated in the plane passing across the longitudinal axis of the specimen. In all of the cases, the length of the metallographic specimen amounted to 50 mm. Such preparation of the joints enabled the obtainment of the constant value of overlay weld surface in the plane of the above named metallographic specimens. For the specimens having a 1 mm thick surfaced layer (nos. 1, 3, 5 and 7 according to Table 3), the area of the overlay weld on the metallographic specimen amounted to 100 mm². For the specimens having a 2 mm thick surfaced layer (nos. 2, 4, 6 and 8 according to Table 3), the area of the overlay weld on the metallographic specimen amounted to 200 mm².

In order to assess the quality of overlay welds, it was necessary to adopt the ratio (expressed in per cent) of the area of welding imperfections of overlay welds detected in the metallographic specimen to the areas of these overlay welds. The area of visible imperfections was measured using a planimeter and

Table 4. Measurement results concerning the area of welding imperfections in the plane of the metallographic specimens

No.	Metallographic specimen designation	Sum of imperfection areas A, mm	Average value of imperfection areas $\bar{A}$, mm²	Overlay weld area s, mm²	Parameter $a = \frac{\bar{a}}{S} \cdot 100$ %
1	1/1	no imperfections	0.081	100	0.081
2	1/2	0.107			
3	1/3	0.216			
4	1/4	no imperfections			
5	1/5	0.082			
6	2/1	0.648	0.921	200	0.461
7	2/2	0.326			
8	2/3	1.361			
9	2/4	0.735			
10	2/5	1.534			
11	3/1	0.069	0.110	100	0.110
12	3/2	0.108			
13	3/3	0.262			
14	3/4	no imperfections			
15	3/5	0.111			
16	4/1	0.523	0.501	200	0.251
17	4/2	0.754			
18	4/3	0.540			
19	4/4	0.394			
20	4/5	0.291			
21	5/1	0.144	0.169	100	0.169
22	5/2	0.202			
23	5/3	0.259			
24	5/4	0.149			
25	5/5	0.088			
26	6/1	2.595	0.910	200	0.455
27	6/2	0.414			
28	6/3	1.011			
29	6/4	0.412			
30	6/5	0.118			
31	7/1	0.077	0.166	100	0.166
32	7/2	0.109			
33	7/3	0.258			
34	7/4	0.386			
35	7/5	no imperfections			
36	8/1	0.650	0.690	200	0.345
37	8/2	0.945			
38	8/3	0.400			
39	8/4	1.030			
40	8/5	0.425			

metallographic specimens magnified 8 times. In order to average results, measurements involved five metallographic specimens in each series of the specimens. The measurement results concerning the areas of imperfections and their ratio to the surface of the overlay weld are presented in Table 4.

Table 4 reveals that the values of the ratio of the average sum of the areas containing detected welding imperfections to the area of the overlay weld (parameter $a = \frac{\bar{a}}{S} \cdot 100\%$) were restricted within the range of 0.081% to 0.461%. The evaluation of overlay weld quality using the above named parameter is uncomfortable. It would be more convenient to use the notion of quality level, similar to the solution adopted in standard PN-EN ISO 5817 *Welding. Fusion-welded joints in steel, nickel, titanium and their alloys (beam welding excluded). Quality levels for imperfections*. For this reason, parameter "a" was used to define three quality levels related to overlay welds. Similar to welded joints, the levels were designated by capital letters of B, C and D and additionally letter N, to inform that the quality levels were concerned with the quality of overlay welds. The quality levels concerning overlay welds (in relation to the value of parameter "a") are presented in Table 5 and Figure 9.

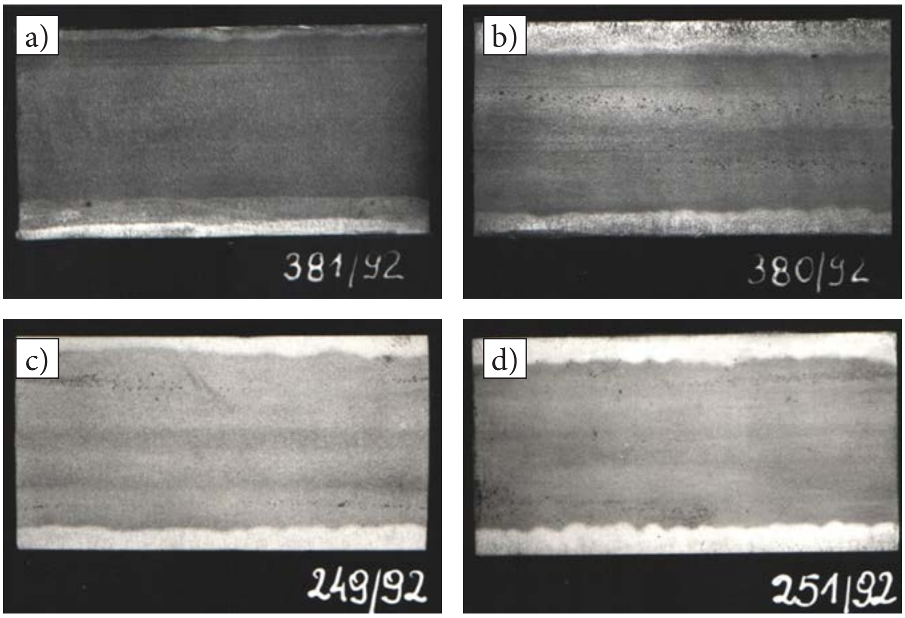

Fig. 8. Examples of macroscopic specimens of the surfaced specimens used in the assessment of overlay welds: a) surfacing performed using process 111, the specimen after normalising, overlay weld thickness g=1 mm; b) surfacing performed using process 111, the specimen after toughening, overlay weld thickness g=2 mm; c) surfacing performed using process 135, the specimen after normalising, overlay weld thickness g=1 mm; d) surfacing performed using process 135, the specimen after toughening, overlay weld thickness g=2 mm

Table 5. Quality levels of overlay welds in relation to parameter "a"

Overlay weld quality level	**NB**	**NC**	**ND**
Value of parameter "*a*", %	a ≤ 0.20	0.20 < a ≤ 0.40	0.40 < a ≤ 0.60

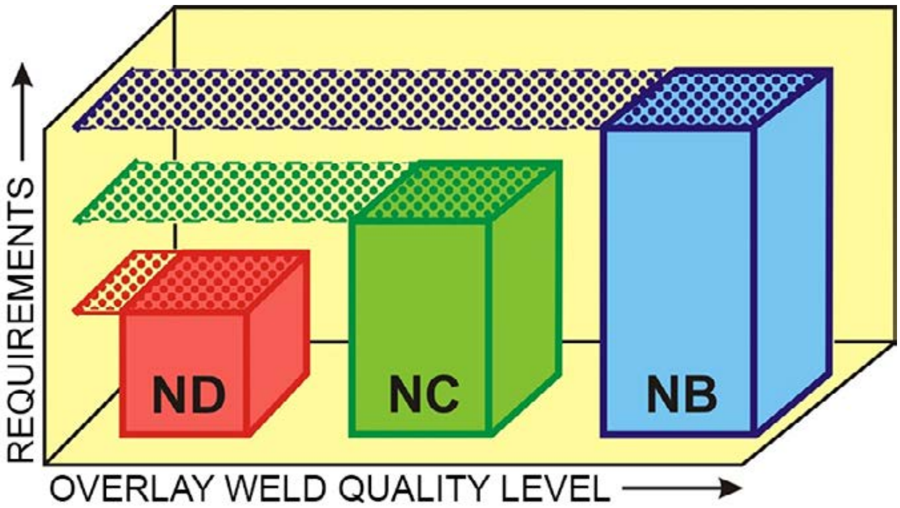

Fig. 9. Quality levels of overlay welds in relation to assigned requirements

As can be seen in Table 5 and Figure 9, quality level NB corresponds to the highest requirements concerning the quality of overlay welds, whereas level ND corresponds to the lowest requirements. Quality level NC corresponds to the intermediate requirements of overlay weld quality.

In accordance with the adopted classification, the test specimens were characterised by various overlay weld quality levels. Specimens designated in Table 3 as 1, 3, 5 and 7 were recognised as representing quality level NB, specimens designated as 4 and 8 were categorised as representing quality level NC, whereas specimens 2 and 6 were found to represent quality level ND.

Summary

The macroscopic tests of the overlay welds revealed the proper penetration of the first layer of the overlay weld into the base material and the proper application of the successive layers. Some overlay welds contained welding imperfections in the form of slight gas pores and slag inclusions. In spite of strictly following the developed surfacing technology and care applied when making individual layers of the overlay welds, the avoidance of the above named imperfections proved impossible.

The NDT results related to the surfaced specimens did not allow the explicit interpretation concerning the quality of overlay weld subsurface layers. Therefore, it can be concluded that the quality of overlay welds should be assessed using destructive tests (usually macroscopic). However, technical reference publications did not contain information related to this issue, which inspired the tests described in this article.

The conducted tests and measurements led to the development of the methodology making it possible to assess the quality of overlay welds on the basis of macroscopic tests as well as led to the development of classification (assessment) criteria concerning the quality of overlay welds. It is suggested that the measure of overlay weld quality be the ratio (expressed in per cent) of the area of welding imperfections (of a given overlay weld) detected in the metallographic specimen to the area of this overlay weld, also revealed in the plane of the metallographic specimen (parameter "a", Table 4). In such a procedure, the making of a macroscopic metallographic specimen is strictly specified. The plane of the metallographic specimen must be situated in the plane passing through the longitudinal axis of the specimen, whereas the length should amount to 50 mm. In order to average results, it is recommended that measurements be performed on 5 metallographic specimens.

The test results enabled the obtainment of averaged values of parameter "*a*" (Table 4), restricted within the range of 0.081% to 0.461%. Parameter "*a*" was used to define three overlay weld-related quality levels designated by capital letters of B, C, D and, additionally, N (Table 5). Quality level ND is characterised by the lowest, whereas quality level NB represents the highest quality. Quality level NC represents the intermediate quality of overlay welds. It should be noted that each quality level has its boundary values in relation to detected welding imperfections. For this reason, it is possible to come across surfaced layers representing worse quality than that characterised by quality level ND. In accordance with the practice applied when assessing the quality of welded joints, it is recommended that such overlay welds be recorded as n.s. ND, i.e. not satisfying the requirements of quality level ND.

The specification of criteria for overlay weld quality assessment enabled evaluating the quality specimens used in the tests. Specimens designated in Table 3 as 1, 3, 5 and 7 were recognised as representing quality level NB, specimens designated as 4 and 8 were categorised as representing quality level NC, whereas specimens 2 and 6 were found to represent quality level ND. No specimens were classified as n. s. ND.

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