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Controlling the Quality and Life of Briquetting Machine MMA Surfaced Working Elements in the Process of Steel Briquette Manufacturing

Abstract: The article presents the results of a study dedicated to the selection of covered electrodes applied for the surfacing of briquetting machine working elements used in the production of briquettes made of fine-grained steel scrap. The analysis of operating conditions and wear mechanisms affecting surfaces of working elements enabled the preliminary selection of four types of covered electrodes used for the surfacing of wear-resistant surfaces. The tests involved structural and chemical composition analyses, microhardness measurements and the analysis of operational properties, particularly of metal-metal abrasive wear in relation to electrode weld deposits. The selection of electrodes, whose weld deposit provides the highest resistance to metal-metal abrasive wear were followed by operational tests of briquetting machine surfaced elements in real production conditions. The tests have revealed that the surfacing of the surfaces of briquetting machine work elements by means of EC 4119 covered electrodes extends the service life of these elements four times if compared with the life of original working elements made of tool steel intended for cold operation.

Keywords: steel briquette manufacturing, MMA surfacing, quality controll

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Introduction

The wear of the surfaces and edges of machinery and tool working elements is natural and inevitable [1-3], leading to a gradual decrease in operating properties, parameters and efficiency which, if happening uncontrollably, can result in damage or failure [4, 5]. The excessive wear issue affecting working elements of technological lines, machines and tools is common in many companies. The SILINGEN POLSKA company deals with raw materials recovery, production of ferroalloy briquettes, steel briquettes and SILANCER® oxygen lances. Presently, over 95% of SILINGEN POLSKA production is exported primarily to Germany, France and the Czech Republic. Also, many Polish companies

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active in the metallurgical, steelmaking, casting and welding sectors show significant interest in the Silingen Polska product range. Presently, the Research and Development Department is focused on the implementation of new briquette-making technologies and on the development of new types of metal briquettes.

The company's development plans assume a gradual increase in the national, European and global market share, and within several years, the construction of a modern production plant using modern achievements in sustainable energy sources and energy recovery solutions in technological processes, maintaining the plant's environmental impact at the lowest possible level.

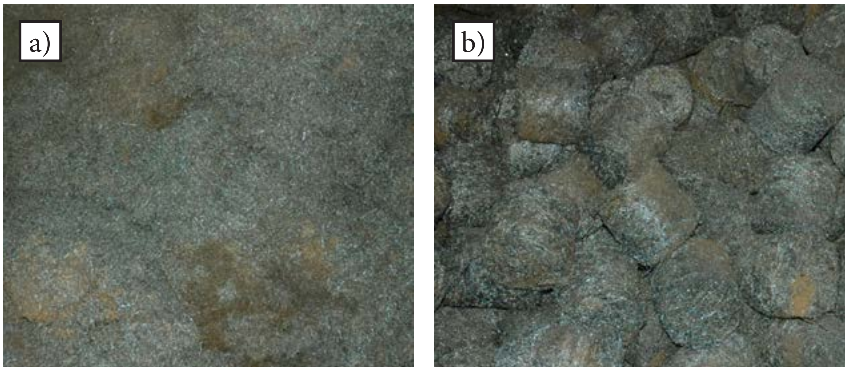

Fig. 1. Loose steel cord (a) and steel briquettes made by multi-stage pressing of fine-grained scrap steel (b)

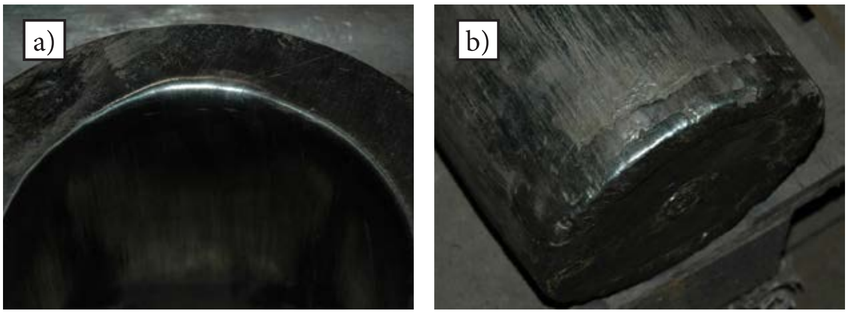

Fig. 2. Worn-out set for forming and pressing briquettes out of steel cord: sleeve (a) and punch (b)

Steel briquettes are made as a result of mechanical processing of fine-grained scarp steel consisting in thickening and pressing; briquettes are primarily used as metallic charge material, so-called metallic charge, fed directly to a metal bath in the process of cast steel melting in steelworks or foundry steelmaking furnaces (Fig. 1) [6]. Therefore, steel briquettes, as finished products of processing and recovering fine-grained scrap steel, constitute a full-value charge material in steelmaking processes, and, at the same time, can be stored, transported without any restrictions and delivered directly to steelworks or other facilities dealing with steel melting and production [7÷9]. Steel briquettes are formed in a cylinder as a result of pressure exerted by the punch (cylinder) of a hydraulic press. Such a briquette-forming method, i.e. multi-stage pressing of fine-grained scrap steel, is responsible for the intense local wear of the surfaces of briquetting machine working elements (Fig. 2, 3).

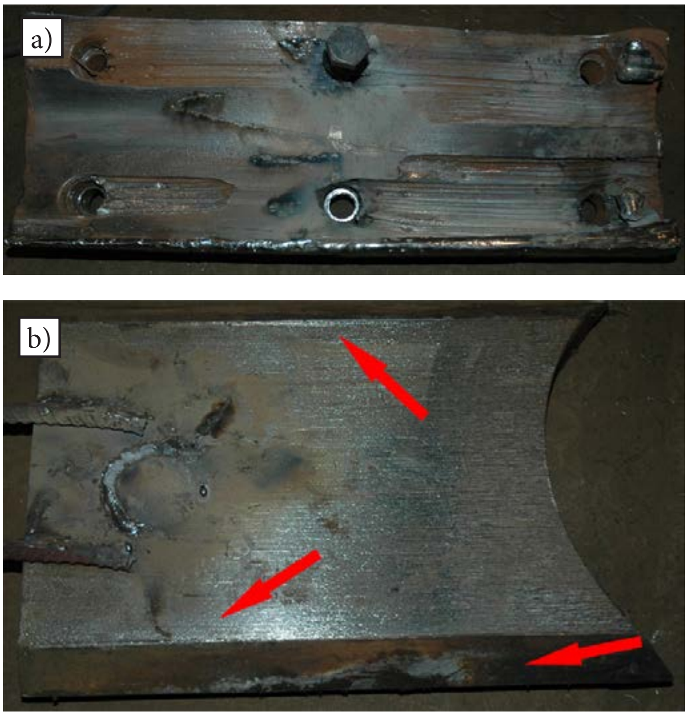

Fig. 3. Worn-out briquetting machine guides after processing merely 700 tons of charge: a) punch guide, b) second-degree pressing guide (traces of non-uniform abrasion of surface)

Test materials and methodology

The tests and visual inspection of briquetting machine working elements, such as the punch guide, punch and forming sleeve, revealed traces of wear easily noticeable on the surface and edges and having the form of longitudinal scratches, abrasions and material decrements

Table 1. Typical chemical composition of ESAB-manufactured EN 400MnB covered electrode weld deposit [10]

Contents of alloying agents, % by weight						
C	Mn	Si	Cr	Mo	W	V
0.9	12.0	0.4	-	-	-	-

Note: low-hydrogen cover, approximate weld deposit hardness: 190÷250 HB (approximately 400 HB after cold peening)

Table 2. Typical chemical composition of ESAB-manufactured EN 600B covered electrode weld deposit [10]

Contents of alloying agents, % by weight						
C	Mn	Si	Cr	Mo	W	V
0.6	1.4	1.2	5.6	-	-	-

Note: low-hydrogen cover, approximate weld deposit hardness: 50÷55 HRC

(Fig. 2, 3). It was also noticed that the wear of the surface and edges of briquetting machine working elements was not uniform (Fig. 2, 3). The highest wear of the sleeve and punch was observed on the guide side, which, at the same time, forces a steel cord into the third-degree chamber where briquettes are pressed and formed (Fig. 2). The analysis of the operation of the briquetting machine working units revealed that they were mainly exposed to static loads at an operating temperature not exceeding 40-50°C. Apart from humidity contained in the charge material and in the air, the working elements were not exposed to the effect of the environment or corrosives. Therefore, the dominant mechanism responsible for the wear and decrements of working elements was abrasive wear caused by the fed and pressed material, i.e. steel cord having the form of steel wires characterised by high hardness (30-40 HRC) (Fig. 1). As a result, it was assumed that a filler metal for surfacing the tested elements of the briquetting machine should be primarily characterised by high hardness, i.e. higher than that of the steel cord wires, i.e. by a minimum of 40 HRC. The tests aimed to select covered electrodes for surfacing the briquetting machine working elements, ensuring the longest possible operating time of the whole production line between successive periodic inspections.

The tests involved the use of a base for surfacing test overlay welds in the form of 10 mm thick plates made of S235 unalloyed steel (100×100 mm) and disks (ϕ 46.0 mm) for testing abrasive wear using the ball-on-disk method, according to ASTM G99. The surfacing tests involved two types of commonly used ESAB-manufactured covered electrodes, i.e. ESAB EN 400MnB and EN 600B (ϕ 4.0 mm), applied for repair and production surfacing of wear-resistant layers (Table 1, 2) and two Castolin-manufactured types of electrodes, i.e. Castolin EC 3292 and EC 4119 (ϕ 3.2 mm), providing high abrasive wear resistance and high hardness of weld deposit [10,11]. According to Castolin-provided information, the hardness of EC 3292 electrode weld deposit amounts to 53÷57 HRC, whereas the hardness of EC 4119 electrode weld deposit can reach even 70 HRC [11]. Manual surfacing tests using covered electrodes were performed on a welding station equipped with an ESAB TIG 150 inverter welding power source.

Following the producer's recommendations, before surfacing, all the electrodes were dried at 200°C for 3 hours, and the surfaces of steel plates and disks were subjected to sand blasting. The steel plate intended for surfacing by means of EC 4119 electrodes (i.e. of the highest weld deposit hardness) were preheated to approximately 300÷400°C, according to the electrode producer's recommendations. The test overlay welds were made using multiple simple runs within the range of parameters recommended for individual electrodes (Fig. 4, 5).

In order to compare the resistance of the overlay welds to dynamic loads, also periodically present during briquetting machine operation, particularly during unstable feeding of charge material, additional tests were performed using a special device enabling the application of a local load by gravitationally dropping a steel ball with an additional load. Multiple drops were performed from an

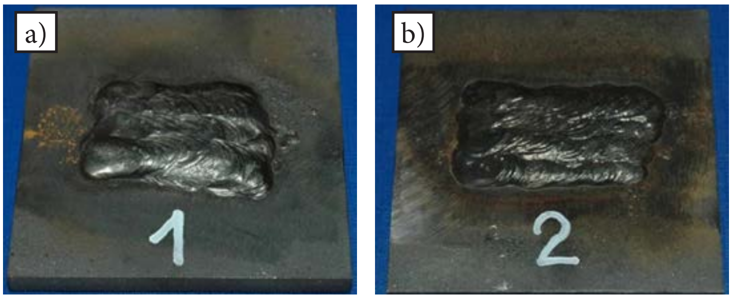

Fig. 4. Steel plates with overlay welds made using ESAB-manufactured covered electrodes: a) EN 400MnB, b) EN 600B

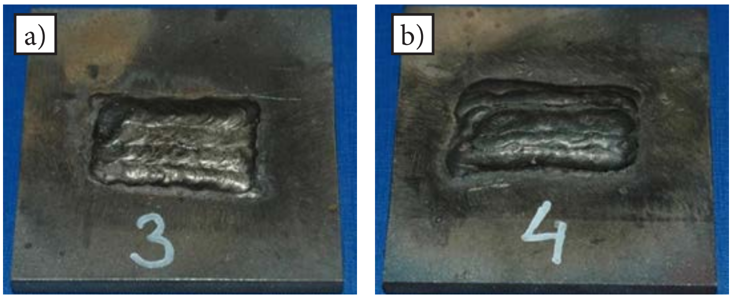

Fig. 5. Steel plates with overlay welds made using Castolin-manufactured covered electrodes: a) EC 3292, b) EC 4119

Fig. 6. Device for testing the resistance of overlay welds to impact loads

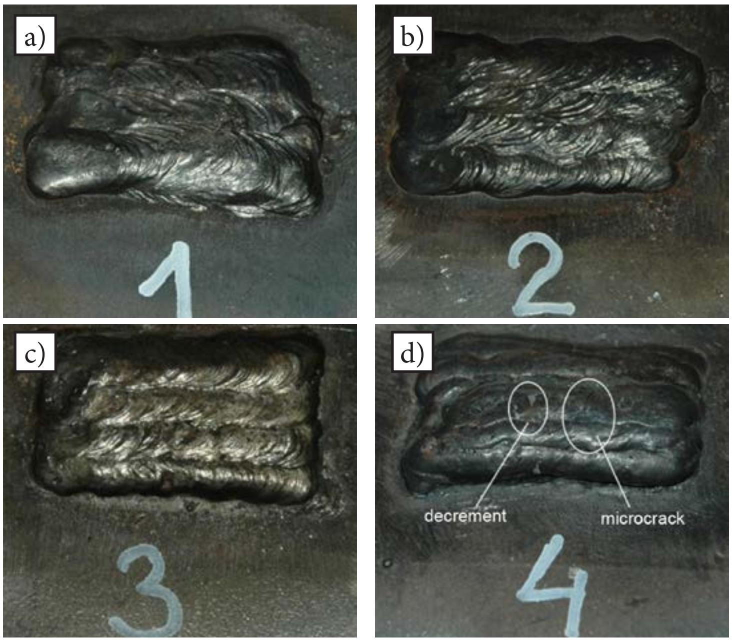

Fig. 7. Overlay welds after impact load resistance tests' overlay welds made using: a) ESAB EN 400MnB electrodes – lack of cracks, b) ESAB EN 600B electrodes – lack of cracks, c) Castolin EC 3292 electrodes – lack of cracks, d) Castolin EC 4119 electrodes – visible longitudinal and transverse cracks and overlay weld decrements (spalls) (Fig. 6, 8)

approximate height of 0.5 m, which made it possible to apply a load of the same and strictly specified kinetic energy (Fig. 6). After each heating, the surface of a given overlay weld was subjected to observation and the photographic documentation of overlay weld strains, cracks and spalls was made (Fig. 7, 8). Due to the fact that after 15 ball drops it was possible to observe decrements of overlay weld no. 4 (made using a Castolin Ec 4119 electrode), for all overlay welds the number of ball drops was limited to twenty.

The impact load resistance tests were followed by hardness measurements involving polished and smoothed overlay weld surface both in areas affected and those not affected by the impact loads (Fig. 13, Table 3).

The subsequent stage of tests involved the preparation of specimens for microscopic observations, metallographic tests and chemical composition determination. The overlay welds were cut transversely in relation to the surfacing direction (i.e. overly weld axis), next were subjected to grinding by means of a plane grinding machine and abrasive papers of various granularities, and finally underwent polishing by means of a diamond slurry. For macroscopic examinations the surfaces of metallographic specimens were etched using the Adler reagent (Fig. 10÷13), whereas for microscopic

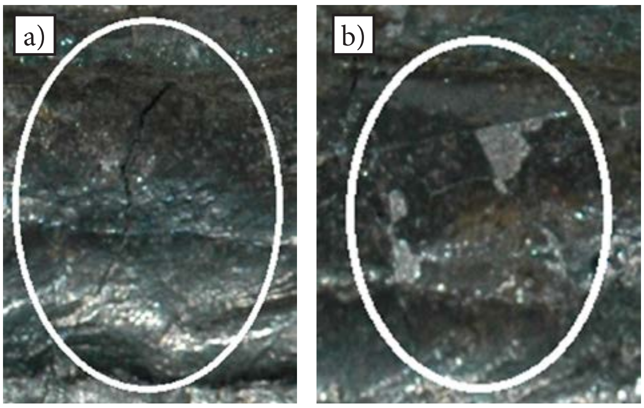

Fig. 8. Transverse cracks (a) and decrements (b) on the surface of the overlay weld made using EC 4119 electrodes, after impact load tests (Fig. 7)

Table 3. HRC hardness measurement results on overlay weld surface (Fig. 9)

No.*	Specimen 1 (EN 400MnB)		Specimen 2 (EN 600B)		Specimen 3 (EC 3292)		Specimen 4 (EC 4119)	
	At impact area	Outside impact area	At impact area	Outside impact area	At impact area	Outside impact area	At impact area	Outside impact area
1	30.1	16.5	43.4	58.1	55.1	48.6	60.5	**62**
2	**32.6**	13.4	50.1	46.7	53	52.2	55.8	58.3
3	28.2	16.1	55.4	**57.6**	49	49.3	**62.6**	33.4
4	29.4	**12.8**	54.5	57.2	**57.7**	52.8	45.2	49.2
5	30.3	17.6	53.7	55.4	56.9	51.3	60.6	60.1
Average value	**30**	**15.28**	**51.42**	**55**	**54.34**	**50.84**	**56.94**	**52.6**

Note: * - successive HRC hardness measurements on the surface of the overlay weld face. In the case of areas subjected to impact loads, hardness was measured after twenty impact load applications

observations they were etched using Nital or an iron chloride ($FeCl_3$) solution (Fig. 14÷17). In turn, chemical composition tests and observations using a scanning electron microscope SEM were performed on unetched surfaces (Fig. 17, 18). The tests and analyses of the chemical compositions of the overlay welds tested were performed using a Zeiss Evo MA10 electron microscope equipped with an EDS Bruker XFlash 5010 spectrometer (Table 4).

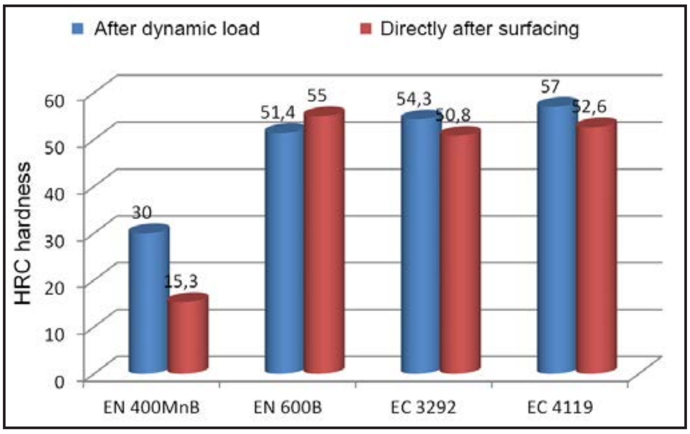

Fig. 9. Comparison of hardness on the surface of the overlay weld face, measured in the areas affected and not affected by impact loads (Table 3)

Fig. 10. Macrostructure of the overlay weld made using an ESAB EN 400MnB covered electrode, etching: Adler's reagent

Fig. 11. Macrostructure of the overlay weld made using an ESAB EN 600B covered electrode, etching: Adler's reagent

Fig. 12. Macrostructure of the overlay weld made using a Castolin EC 3292 covered electrode, etching: Adler's reagent

Fig. 13. Macrostructure of the overlay weld made using a Castolin EC 4119 covered electrode, (visible overlay weld metal porosity), etching: Adler's reagent

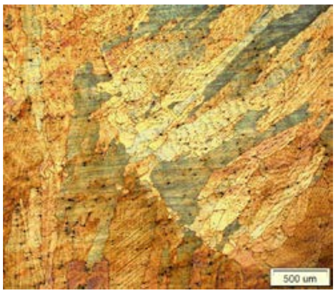

Fig. 14. Microstructure of the central area of the overlay weld made using an ESAB EN 400MnB covered electrode

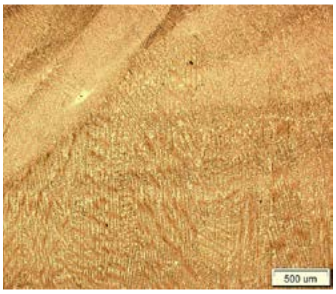

Fig. 15. Microstructure of the central area of the overlay weld made using an ESAB EN 600B covered electrode

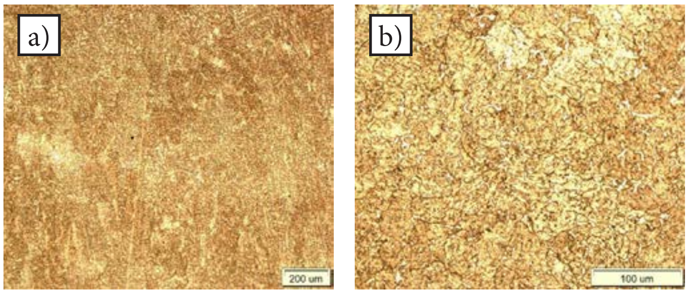

Fig. 16. Microstructure of the central area of the overlay weld made using a Castolin EC 3292 covered electrode: a) mag. 100x, b) mag. 200x

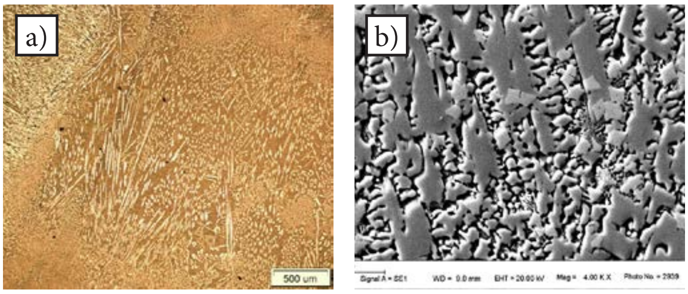

Fig. 17. Microstructure of the central area of the overlay weld made using a Castolin EC 4119 covered electrode:a) image recorded using a light microscope, b) image recorded using a scanning electron microscope (SEM)

Table 4. Results of overlay weldchemical composition analysis

Electrode designation	Contents of alloying agents (average), % by weight					
	Fe	C	Mn	Si	Cr	Others
EN 400MnB	rest	0.7	11.3	0.35	-	-
EN 600B	rest	0.47	1.8	1.17	3.8	-
EC 3292	rest	0.8	5.5	1.08	8.9	-
EC 4119	rest	4.1	3.9	0.3	13.5	Nb<3.9, Ti<2.1

Abrasive wear resistance tests performed using the ball-on-disk method and a T-01M tester, were conducted in the laboratory of the Department of Welding at the Silesian University of Technology (Fig. 19). The tests involved the use of specimens in the form of disks (ϕ 46.0 mm), in accordance with ASTM G99 (Fig. 20, 21).

The analysis of the test results related to the abrasive wear resistance of the weld deposit of electrodes (overlay welds) made in laboratory conditions using the ball-on-disk method revealed that the highest wear resistance was characteristic of the overlay welds made using

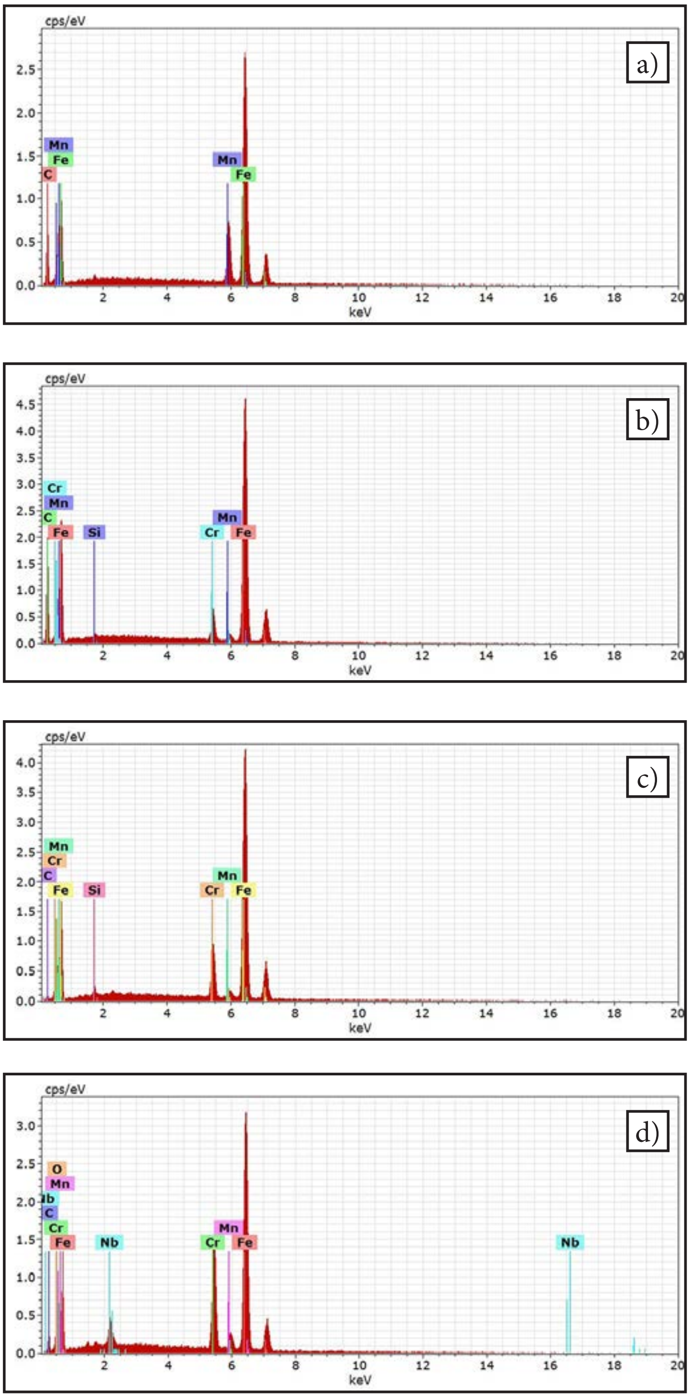

Fig. 18. Energy dispersive spectrum (EDS) of the area of the overlay weld made using: a) ESAB EN 400MnB, b) ESAB EN 600B, c) Castolin EC 3292, d) Castolin EC 4119 covered electrodes

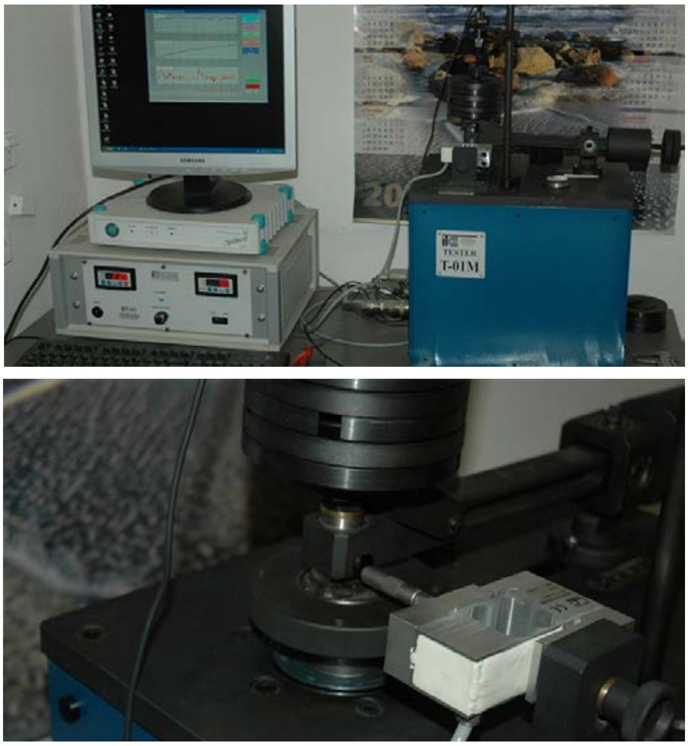

Fig. 19. T-01M tester for testing abrasive wear resistance using the ball-on-disk method

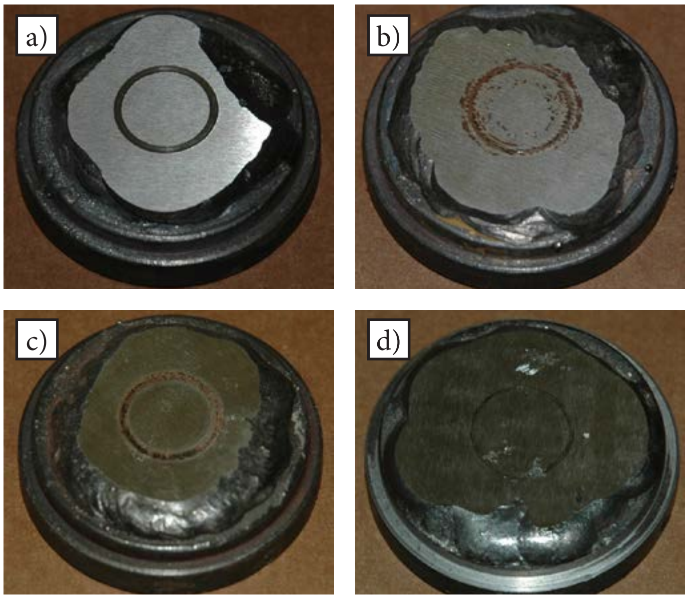

Fig. 20. Specimens in the form of disks with overlay welds after abrasive wear resistance tests performed using the ball-on-disk method; overlay welds made using a) ESAB EN 400MnB electrodes (visible significant surface abrasion), b) ESAB EN 600B, c) Castolin EC 3292, d) Castolin EC 4119 (narrowest trace on the surface tested)

Castolin Ec 4119 covered electrodes (Fig. 20, 21). For this reason, it was decided that further operational tests in actual operating conditions of the briquetting machine would be performed using working elements of surfaces subjected to surfacing by means of Castolin Ec 4119 covered electrodes. The operational tests involved the briquetting machine punch guide as it is operated in very difficult conditions of intensive abrasion by a pressed steel cord with simultaneous significant unitary pressure (Fig. 22). In addition, the operating principle and the design of the briquetting machine provides easy access to the punch guide (unlike other working elements such as the punch and the sleeve) allowing the monitoring of its wear.

Summary

The visual tests revealed that the overlay welds made using Esab En 400MnB, En 600B and Castolin Ec 3292 covered electrodes were of proper shape and their faces were free from cracks and incomplete fusions (Fig. 4, 5). In turn, the test overlay weld made using Castolin Ec 4119 covered electrodes was characterised by a very smooth face surface, yet it contained several longitudinal and transverse cracks at half its length (Fig. 5). According to

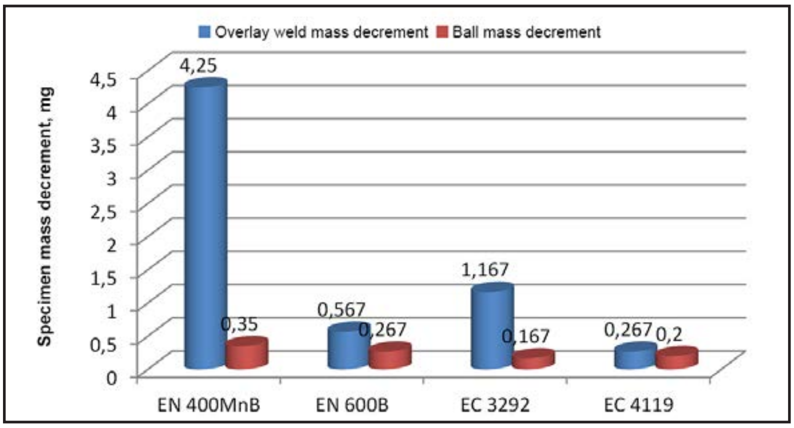

Fig. 21. Test results related to abrasive wear resistance of test overlay welds made using the ball-on-disk method (Fig. 19, 20)

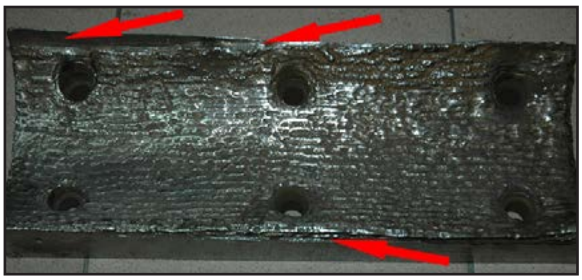

Fig. 22. Briquetting machine punch guide with the work surface surfaced using Castolin EC 4119 covered electrodes after processing 2.5 thousand tons of fine-grained scrap steel (steel cord). Wear traces visible only on the external edges of the guide

information provided by the manufacturer of these electrodes, due to the very high hardness of the Ec 4119 electrode weld deposit, cracks of overlay weld face surfaces are allowed and can be present even after preheating [11].

The tests of overlay weld resistance to impact loads performed by multiple load applications using a steel ball freely falling from a height of 0.5 m revealed that the face of the overlay weld made using Esab En 400MnB covered electrodes underwent a slight plastic strain each time after being hit by the ball (Fig. 6, 7). At the same time, impact load applied many times (20x) (Fig. 7) did not lead to the formation of any cracks on the face surface. In turn, the overlay welds made using Esab En 600B and Castolin Ec 3292 covered electrodes were even free from plastic strains on the face surface areas hit by the steel ball (Fig. 7). The face surface was also free from cracks after the application of multiple (20x) impact loads. The test overlay weld made using Castolin Ec 4119 covered electrodes revealed the propagation of cracks each time after the overlay weld was hit by the ball; the face revealed the presence of successively formed cracks and microcracks (Fig. 7). In addition, repeated hitting with the ball led to the overlay weld decrement (spalling).

Hardness measurements of the overlay welds, performed on the overlay weld face areas subjected to multiple impact loads and outside these areas, revealed that in the case of the overlay weld made using Esab En 400MnB covered electrodes, the hardness of overlay weld face surface was low, slightly exceeding 15.0 HRC (Fig. 9, Table 3). In turn, in the areas repeatedly hit by the steel ball, hardness almost doubled and amounted to approximately 30 HRC, with single hardness measurement results reaching even 32.6 HRC (Fig. 9, Table 3). The hardness measurement results revealed that the weld deposit of Esab En 400MnB electrodes was characterised by high plasticity and toughness with susceptibility to impact load-induced hardening and development of plastic strains, similar as in the case of the Hadfield cast steel behaviour (Fig. 9, Table 3). The overlay welds made using Esab En 600B, Castolin Ec 3292 and Ec 4119 covered electrodes did not reveal similar susceptibility to overlay weld hardening caused by impact load (Fig. 9, Table 3). The maximum hardness of the overlay welds made using Esab En 600B electrodes amounted to 58.1 HRC, of the overlay welds made using Castolin Ec 3292 electrodes amounted to 57.7 HRC, and of the overlay welds made using Castolin Ec 4119 electrodes amounted to 62.6 HRC (Fig. 9, Table 3). As regards the overlay welds made using Castolin Ec 4119 covered electrodes, the Vickers hardness test was difficult due to cracks and microcracks, which during measurements and indenter loading caused the propagation of existing cracks and the formation of new cracks. As a result, the average value of measurements was encumbered with significant error due to the substantial scatter of measurement results (Table 3).

The metallographic tests and macroscopic observations of the overlay welds revealed proper penetration into the base material (BM) and the proper shape of the fusion lines of all the overlay welds, the slight content of the base material in the overlay welds, and the high quality (freedom from cracks, inclusions or porosity) of the overlay welds made using Esab En 400MnB, En 600B and Castolin Ec 3292 electrodes (Fig. 10÷13). In turn, the overlay weld made using Castolin Ec 4119 electrodes revealed the presence of single gas pores in some overlay weld runs (Fig. 13).

The examinations of the chemical compositions of overlay welds revealed that the overlay weld made using Esab En 400MnB electrodes contained approximately 10-20% of manganese (Table 4, Fig. 18) (being also the primary alloying agent). Such a high manganese content, as well as significant overlay weld hardening due to dynamic load and plastic strain confirmed that the weld deposit was characterised by the chemical composition and properties close to those characterising the Hadfield cast steel. The microscopic analysis revealed the coarse-grained structure containing long columnar crystals perpendicular the fusion line and accruing in the direction the overlay weld face (Fig. 10, 14). The length of single crystals exceeded 1.5 or even 2.0 mm (Fig. 10, 14).

The chemical composition of the overlay weld made using Esab En 600B electrodes was different from the previous one as it only contained approximately 4.0-5.0% of manganese and, additionally, approximately 4.0% of chromium and a slight amount of silicon (Fig. 11, 15, Table 4). The overlay weld structure was also different from the previous one as the size of dendrites was significantly smaller (Fig. 11, 15). The tests of the chemical composition of the overlay weld made using Castolin EC 3292 electrodes revealed the presence of manganese, chromium and silicon, similar to the overlay weld made using Esab En 600B electrodes, yet the contents of those components were significantly higher (Table 4, Fig. 16). In turn, the overlay weld microstructure was fine-grained and similar to the microstructure of the overlay weld made using Esab En 600B electrodes (Fig. 12, 16). The microstructure of the overlay weld made using a Castolin EC 4119 electrode was different from the microstructure of the previously examined overlay welds (Fig. 13, 17). The microstructural analysis revealed that the overlay weld was composite and contained chromium carbides in the metallic matrix (Table 4, Fig. 17, 18). The chemical composition analysis revealed that the overlay weld made using Castolin Ec 4119 electrodes contained over 13% chromium and, at the same time, a significant amount of carbon, i.e. approximately 4.0% (Fig. 17, 18, Table 4).

The tests involving the overlay weld resistance to metal-metal type abrasive wear using the ball-on-disk method revealed that the lowest resistance was that of the overlay weld made using Esab En 400MnB electrodes; the overlay weld was characterised by the structure and properties similar to those of the Hadfield cast steel (Fig. 20, 21). In the case of this overlay weld, the disk mass decrement was the greatest and amounted to 4.25 mg (Fig. 21). Four times smaller (1.167 mg) was the specimen mass decrement observed for the overlay weld made using Castolin Ec 3292 electrodes (Fig. 20, 21). Even higher resistance to metal-metal type abrasive wear was observed for the overlay weld made using Esab En 600B electrodes (Fig. 20, 21)., where the overlay mass decrement amounted to a mere 0.567 mg (Fig. 21). The highest resistance to metal-metal type abrasive wear was characteristic of the overlay weld made using Castolin Ec 4119 electrodes (Fig. 20, 21). This overlay weld was also characterised by the highest hardness of 62.6 HRC, with a composite structure containing acicular chromium carbides seated in metallic matrix (Fig. 17, 21). The mass decrement in the overlay welds made using Castolin Ec 4119 electrodes amounted to a mere 0.267 mg, i.e. almost twenty times lower than in the overlay welds made using Esab En 400MnB electrodes and almost two times lower than in the overlay welds made using Esab En 600B electrodes. In turn, the operational tests of the briquetting machine punch guide with the surfaced work surface revealed that the use of Castolin Ec 4119 electrodes significantly (by 400%) extended the guide service life, if compared with the life of original guide made of tool steel intended for cold operation (Fig. 22).

Conclusions

The MMA arc surfacing tests involving covered electrodes used for surfacing wear-resistant layers and the examinations of structure, chemical composition and operating properties of the overlay welds led to the following conclusions:

- in the test conditions, the highest resistance to metal-metal type abrasive wear characterised the overlay weld made using Castolin Ec 4119 electrodes. The abrasive wear resistance of this overlay weld was twenty times higher than that of the overlay weld made using Esab En 400MnB electrodes (the weld deposit of which was in terms of chemical composition and properties similar to the Hadfield cast steel) and almost two times higher than the wear resistance of the overlay weld made using Esab En 600 electrodes,

– overlay weld made using Castolin Ec 4119 electrodes was also characterised by the highest hardness of 62-63 HRC, if compared with approximately 54-55 HRC characterising the overlay welds made using Esab En 600B and Castolin Ec 3292 electrodes,
– structure of the overlay weld made using Castolin Ec 4119 electrodes was different from the homogenous structures of the other overlay welds tested. The microstructure of this overlay weld was fine-grained and composed of acicular carbides precipitated during overlay weld crystallisation and seated in the metallic matrix,
– - surfacing of briquetting machine working elements used in the production of steel briquettes made of fine-grained scrap steel using Castolin Ec 4119 covered electrodes can extend the service life of these elements by four times if compared with the life of original working elements made of tool steel intended for cold operation.

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