

# CHARACTERIZATION AND COMPARISON OF THE CARBIDES MORPHOLOGIES IN THE NEAR SURFACE REGION OF THE SINGLE - AND DOUBLE LAYER IRON - BASED HARDFACED COATINGS

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**Abstract.** The properties of the high-chromium white iron (HCWI) hardfaced materials, such as hardness, toughness and wear resistance, are affected by the morphology of their reinforcing phase, the Cr-carbides. In this work, the influence of the 1) welding parameters, 2) welding procedures and 3) chemical composition on the near-surface Cr-carbides morphology is presented. Additionally, the effects of the Nucleo C<sup>®</sup> formula (Castolin Eutectic Ltd.) of unknown composition are evaluated. The hardfaced coatings are deposited by using the Submerged Metal Arc Welding (SMAW) Process. The obtained near-surface structures are observed with scanning electron microscope with energy dispersive system (SEM-EDS). The structure morphological parameters are quantitatively determined by use of the ImageJ software. In the single-layer HCWI hardfaced coatings, larger heat input per unit length ( $\approx 4.1$  kJ/mm) is leading to a formation of the hypoeutectic structures. An approximately two times lower heat input ( $\approx 1.8$  kJ/mm) stimulates the solidification of the near-eutectic structures with presence of spheroidized eutectic and primary Cr-carbides (the Nucleo C<sup>®</sup> effect). The double-layer coatings deposited with the  $\approx 1.8$  kJ/mm possess the hypereutectic structures with blade-like primary and needle-like eutectic carbides (the absence of the Nucleo C<sup>®</sup> effect). The lower heat input ( $\approx 1.4$  kJ/mm) and increase of the chromium and carbon content result in a formation of the hypereutectic structures with presence of the primary rod-like Cr-carbides embedded in the eutectic matrix with coarser and irregular eutectic Cr-carbides. The influence of the Nucleo C<sup>®</sup> formula on the Cr-carbides morphology is more pronounced in the single-layer HCWI hardfaced coatings than in the double-layer coatings.

**Keywords:** hardfacing, high chromium white iron, chromium carbides, morphology, SEM-EDS

## 1. Introduction

The addition of carbon increases the volume fraction of the primary chromium carbides in the HCWI hardfaced materials and it has the opposite effect regarding their size and interparticle distance [1]. Furthermore, it changes the morphology of the primary carbides from the blade-like towards the rod-like morphology [2]. These two studies show the increased abrasive wear resistance with addition of carbon, i.e. with increased volume fraction of the primary

chromium carbides. However, this approach is limited due to a degradation of the fracture toughness of HCWI hardfaced coatings with increased carbides volume fraction [3]. The wear resistance and especially toughness of the HCWI hardfaced materials can be improved by refining the primary chromium carbides. The refinement is achieved by addition of the elements or particles that form bases for heterogeneous nucleation of the primary chromium carbides. It can be done either by a smaller addition of the strong carbide-

forming elements, such as titanium [4,5], or by addition of the rare earth elements, such as cerium [6,7], or rare earth oxides, such as cerium oxide [8], or by other means. In the case of the Fe-25Cr-4C hardfacing alloy, a higher wear resistance is achieved by addition of the Ti up to 2 wt.%, which also produced a noticeable refinement of the primary chromium carbides as well as the 3% decrease of their volume fraction [4]. At higher contents, titanium acts as the carbon consumer rather than the primary carbides refiner. The addition of the rare earth elements or rare earth oxides, on the one hand, reduces the size of the primary chromium carbides and their interparticle distance and, on the other hand, enhances their spheroidization and increases their volume fraction. The addition of either cerium or cerium oxide does not lead to the formation of new carbides, but rather to formation of Ce<sub>2</sub>O<sub>2</sub>S. The lattice misfit calculations have shown that Ce<sub>2</sub>O<sub>2</sub>S act as a middle-effective heterogeneous nucleation site for the formation and subsequent growth of the primary chromium carbides.

The studies related to welding procedural effects show the lower abrasive wear resistance [3], lower fracture resistance and lower adhesive strength [9] of the double-layer HCWI hardfaced coatings in comparison to the single-layer coatings. Up to date, the research studies poorly address the welding procedural effects on the

morphology of the primary chromium carbides in the HCWI hardfaced coatings that contain the heterogeneous nucleation additives.

This study examines 1) the influences of the different welding parameters and welding procedures on the near-surface carbides morphology of the HCWI hardfaced coatings, 2) the chromium carbides morphologies in the Nucleo C®-containing single- and double-layer HCWI hardfaced coatings and 3) the carbides morphologies in the Nucleo C®-containing double-layer HCWI hardfaced coatings with different carbon and chromium content.

## 2. Experimental

Hardfacing (deposition by welding) is carried-out on the hot-rolled steel plates of dimensions 250×200×15 mm. Their average chemical composition is determined by the Optical Emission Spectrometer (OES) (Table 1). Castolin Eutectic Co. Ltd, Vienna is the manufacturer of the filler materials used in this study (Table 2). Unlike the 4541 filler material, the 5006 contains the Nucleo C® formula of unknown composition and content. In contrast to the 4541 and 5006 filler materials, the Nucleo C®-containing 6710 has a higher carbon and chromium content (Table 2).

Table 1 Average chemical composition of the steel substrates

Designation	Chemical elements									
	C	Si	Mn	P	S	Cr	Al	Cu	Ni	Fe
This work	0.20	0.55	1.60	0.035	0.035	0.30	0.020	0.30	0.30	balance
S355J2G3 (EN)	≤0.25	≤0.40	-	≤0.04	≤0.05	-	-	≥0.2	-	balance

Table 2 Properties of the filler materials

Commercial designation	Nominal weld metal chemical composition (Cr/C and Cr/Fe wt.% ratio)	Product type (shielding method)	Weld metal hardness	Notice on the weld metal composition
EC 4541®	Fe- Cr-C- Si (8.9 and 0.5)	Basic electrode (gas and slag protection)	≈ 59 HRC	-
Xuper AbraTec 5006®	Fe-Cr-C-S (9.0 and 0.5)	Basic electrode (gas and slag protection)	≈ 59 HRC	The same composition as 4541 + Nucleo C® formula
AbraTec XHD 6710®	Fe-Cr-C-Si / 0.2 Ti (7.0 and 0.6)	Rutile electrode (gas and slag protection)	≈ 65 HRC	The same composition as 5006 + 1.5-2 times higher carbon content and 5 wt.% higher chromium content

Prior to hardfacing, each steel substrate was ground with a grinding machine to remove the existing surface rust. The SiC abrasive papers are used for more detailed rust removal. The 4541 welding electrodes are dried at 623 K (350 °C), the 5006 at 523 K (250 °C) and the 6710 at 423 K (150 °C). The drying time was 2h and the drying atmosphere was the ambient air. The preheating of the steel substrates is performed by using the oxyfuel flame burner. The preheating temperature

was between 433 K (160 °C) and 453 K (180 °C). The filler materials are deposited by using the Shielded Metal Arc Welding (SMAW) process. The hardfacing parameters are given in Table 3. In the case of double-layer coatings, the interpass temperature was maintained between 453 K (180 °C) and 493 K (220 °C). Upon the hardfacing, coatings were air-cooled down to the room temperature.

Table 3 The hardfacing parameters

Parameters	Welding technique		
	SMAW		
	Filler materials		
	4541	5006	6710
Electrode diameter	Ø 4.0 mm	Ø 3.2 mm	Ø 3.2 mm
Current intensity, I [A]	159-161	150-152	119-121
Voltage, U [V]	50-51	25-27	25-26
Welding speed, v [cm/min]	10-12	10-12	10-12
Heat input per unit length, q [kJ/mm]	3.5-4.7	1.7-1.9	1.3-1.5

The effects of the different welding parameters are estimated by comparing the near-surface carbides morphologies of the single-layer 4541 (4541/1) and 5006 (5006/1) hardfaced coatings. The 4541/1 was deposited with the heat input per unit length that is twice as that for the 5006/1. The effects of the welding procedure (in terms of the single and double hardfacing) and the Nucleo C® formula are assessed by analyzing the single-layer 5006 (5006/1) and the double-layer 5006 (5006/2) hardfaced coatings that are deposited with approximately the same heat input per unit length. The influence of the different carbon and chromium content in the Nucleo C®-containing hardfaced materials is investigated by comparing the double-layer 6710 (6710/2) and 5006 (5006/2) hardfaced coatings.

Samples for structure characterization are obtained by cutting the hardfaced materials perpendicular to their surface. The obtained cross-sections are ground with SiC abrasive papers down to P-1200 and polished with alumina suspensions down to 1 µm. The polished surfaces are analyzed by using the scanning electron microscope (SEM) equipped with energy dispersive system (EDS). The SEM-EDS analysis was performed at University of Belgrade – Faculty of Mining and Geology (UB-RGF) by using the JEOL JSM-6610LV SEM connected with the INCA350 energy-dispersion X-ray analysis unit. The electron acceleration voltage of 20 kV and the tungsten filament were used. Before SEM-EDS analysis was performed,

polished surfaces were 20 nm gold coated in a vacuum chamber by use of a sputter coater device.

The morphological parameters of the near-surface carbides, that is, the volume fraction, Feret's diameter, perimeter, edge-to-edge (E-t-E) interparticle distance and roundness, are determined by using the ImageJ software for image analysis [10]. For all parameters, except the volume fraction, the cumulative frequency (CF) distribution functions were produced. By using the 75% cumulative frequency mode, the values of the morphological parameters were determined.

### 3. Results and Discussion

The typical near-surface structures, obtained after hardfacing, are presented in Figure 1. The Figure 1a shows the structure of the 4541/1. More than a half of the phases present are the primary austenite dendrites and the rest is the lamellar eutectic mixture of austenite and Cr-carbides (Table 4). The 5006/1 during solidification achieves the near-eutectic structure (Figure 1b). The presence of the small spherical primary Cr-carbides is observed (9.1 vol.%) in the eutectic matrix (90.9 vol.%). An approximately two times lower heat input per unit length (Table 3) increases the total volume fraction of the Cr-carbides in the 5006/1 coatings by a factor of two in comparison to the 4541/1 (Table 4). The Feret's diameter, perimeter and E-t-E interparticle distance of the 5006/1 eutectic Cr-carbides are insignificantly changed, but the roundness is three times higher than that of the 4541/1 eutectic carbides (Figure 2). Such differences in the total

carbides volume fraction and roundness as well as uniform distribution of the Cr-carbides in the 5006/1 coatings (Figure 1b) indicate on the existence of a larger number of sites for nucleation of Cr-carbides and a fast nucleation rates. This effect can be assign to the Nucleo C® formula. It is similar to the effect of the cerium oxide particles addition [8] and opposite to the effect of the titanium addition [4,5]. In contrast to titanium, which consumes carbon to form the nucleation sites, the cerium oxide addition increases the volume fraction of the Cr-carbides (Section 1).

The deposition of the second layer (5006/2) of the Nucleo C®-containing material onto the surface of the 5006/1, with similar heat input per unit length (Table 3), does not lead to a significant change of the primary nor eutectic Cr-carbides volume fraction (Table 4.). However, the appreciable change of all morphological parameters of both eutectic (Figure 2) and primary (Figure 3) Cr-carbides can be observed. Further

more, the amount of change of the eutectic Cr-carbides morphological parameters is the similar to the amount of change of the primary Cr-carbides morphological parameters. It seems as that the spherical Cr-carbides in the 5006/1 (Figure 1b) act as a nucleation sites for the new Cr-carbides in the 5006/2 hardfaced coatings (Figure 1c). In other words, the effect of the Nucleo C® formula is absent. The dominant presence of blade-like primary carbides confirms this assumption. In addition, the eutectic carbides have a needle-like appearance. The roundness parameter is decreased three to four times in both cases and the sizes of eutectic and primary Cr-carbides are severaly increased. The differences in primary Cr-carbide sizes and their E-t-E interparticle distances between 5006/1 and 5006/2 will probably lead to differences in their abrasive wear behaviour. The dispersed carbides in the case of 5006/1 should more effectively protect the softer matrix.

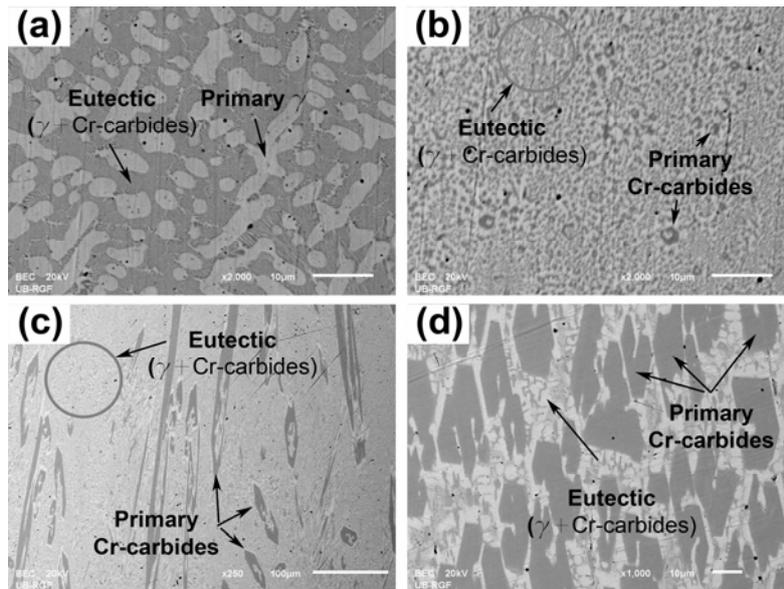


Figure 1 The near-surface structures of the (a) 4541/1, (b) 5006/1, (c) 5006/2 and (d) 6710/2 hardfaced coatings; back-scattering electron images.

Table 4 Phase composition in the hardfaced coatings (vol.%).

Phase	Hardfaced coating			
	4541/1	5006/1	5006/2	6710/2
Primary austenite	50,7	--	--	--
Eutectic austenite	22,8	57,4	53,2	43,8
Total austenite	73,5	57,4	53,2	43,8
Primary carbides	--	9,1	11,2	47,3
Eutectic carbides	26,5	33,5	35,6	8,9
Total carbides	26,5	42,6	46,8	56,2

In comparison to the 5006/2 hardfaced coatings, the addition of carbon and chromium

(Table 2) and somewhat lower heat input per unit length (Table 3) leads to an approximately 10%

increase of the total Cr-carbides volume fraction (Table 3). The structure of the obtained 6710/2 coatings comprises a larger rod-like primary Cr-carbides with the total absence of the blade-like type of morphology. This results are in agreement with previous research findings [2] in which the addition of carbon facilitates transition from blade-like towards the rod-like morphology. The rod-like morphology is superior when wear applications are considered. The increase of the

Cr-carbides volume fraction is probably the result of the carbon and chromium addition. It should be pointed out that there are no published results that deal with the influence of carbon and chromium content on the primary Cr-carbides morphology in a presence of the heterogeneous nucleation additives, such as Nucleo C<sup>®</sup> formula. The absence of the blade-like morphology can be the effect of the Nucleo C<sup>®</sup> formula, but this assumption needs to be confirmed.

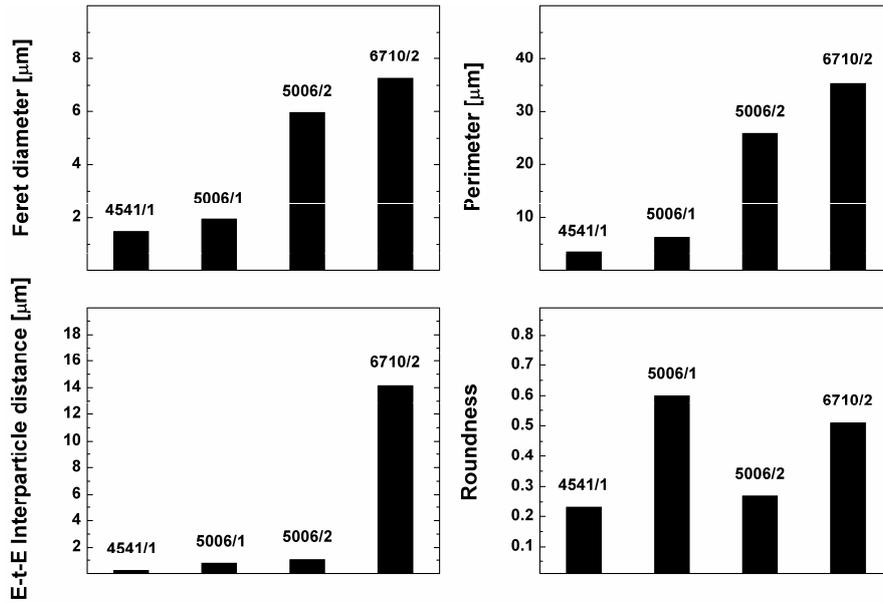


Figure 2 The morphological parameters of the eutectic Cr-carbides in hardfaced coatings.

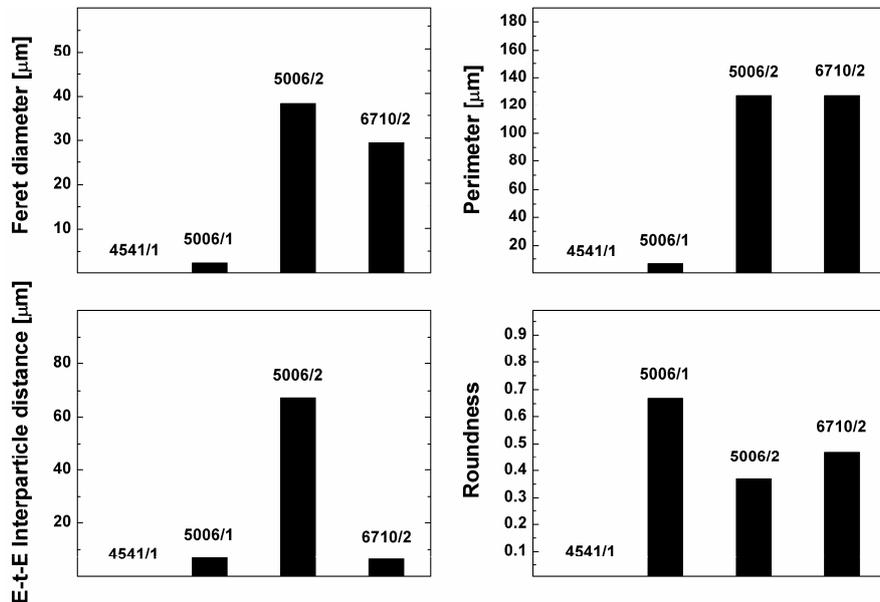


Figure 3 The morphological parameters of the eutectic Cr-carbides in hardfaced coatings

#### 4. Conclusions

In the single-layer HCWI hardfaced coatings, the two times lower heat input per unit length results in the change of solidification mode from hypoeutectic to near-eutectic. The total

volume fraction of the Cr-carbides is doubled and the roundness parameter is tripled. The Cr-carbides are spheroidized, which is probably the effect of the Nucleo C<sup>®</sup> formula. In the double layer Nucleo C<sup>®</sup>-containing HCWI coatings the

same heat input does not significantly influence the carbides volume fraction. However, the values of all morphological parameters are appreciably changed. The sizes of the primary and eutectic Cr-carbides are approximately four and two times larger, respectively. The primary Cr-carbides have the blade-like and the eutectic Cr-carbides the needle-like appearance. The roundness parameter is decreased by a factor of three. The effect of the Nucleo C<sup>®</sup> formula is absent. By increasing the carbon and chromium content, the blade-like morphology of the primary Cr-carbides is replaced by the rod-like morphology. The influence of the Nucleo C<sup>®</sup> formula on the Cr-carbides morphology is more pronounced in the single-layer HCWI hardfaced coatings than in the double-layer coatings.

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## CARACTERIZAREA ȘI COMPARAREA MORFOLOGIILOR CARBIDELOR PREZENTE ÎN VECINĂTATEA SUPRAFETEI ACOPERIRILOR DURE DE PROTECȚIE ÎN SIMPLU ȘI DUBLU STRAT BAZATE PE FIER

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