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COMPOSITES THEORY AND PRACTICE

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THE STRUCTURE OF Ni-TiC COMPOSITE COATINGS DEPOSITED BY PPTAW METHOD

In this paper, the structure investigations of Ni-TiC composite coatings deposited on low carbon steel (S355J0) using plasma powder transferred arc welding (PPTAW) are presented. A blend of nickel alloy powder with 40 vol% TiC was selected as the precursor material for fabricating Ni-TiC composite coatings. The obtained composite layers were characterized by macro and microstructural examination. The distribution of carbide grains in the nickel matrix was characterized by fractal analysis. In addition, the volume fraction of TiC inclusion in the nickel matrix and coating dilution as a function hardfacing parameters were calculated. Metallographic examination revealed that the coatings obtained within the range of a 60÷80 A welding current have discontinuities in the interface layer - substrate and a number of large air bubbles. The composite coatings obtained with a welding current higher than 80 A were correctly formed. The microstructure of the composite coatings contains large and small irregular titanium carbide particles. As a result of the interaction between the nickel alloy matrix and high energy plasma arc with titanium carbide during the surfacing process, small particles are formed. Both the dilution coefficient and volume fraction of TiC increase with an increase in welding current. The last part of the paper includes the results of the fractal dimension measurements of coating cross-sections. For the analyzed structures, the percentage of TiC and linear fractal dimension were determined using the line counting dimension method (LCD), which is a modification of the box counting dimension method (BCD).

Keywords: **composite coatings Ni-TiC, plasma powder transferred arc welding method (PPTAW), fractal analysis**

STRUKTURA KOMPOZYTOWYCH POWŁOK Ni-TiC NAPAWANYCH METODĄ PPTAW

W artykule przedstawiono wyniki badań struktury kompozytowych powłok Ni-TiC otrzymanych metodą napawania plazmowego (ang. PPTAW - Plasma Powder Transferred Arc Welding) w zależności od natężenia prądu napawania. Napoiny te uzyskano w wyniku topienia mieszaniny proszków, w której osnową był proszek na bazie niklu, natomiast fazę umacniającą stanowił proszek TiC. Proszek osnowy mieszano z proszkiem węglika tytanu o tej samej ziarnistości w stosunku objętościowym 60:40. Kompozytowe powłoki napawano na podłoża ze stali niskowęglowej S355J0. Przeprowadzono badania makro- i mikroskopowe otrzymanych napoin kompozytowych Ni-TiC. Zaadaptowano program do analizy obrazów mikroskopowych MultiScanBase do określenia udziału cząstek fazy umacniającej osnowę oraz obliczenia udziału metalu podłoża w napoinie. Do określenia rozmieszczenia cząstek TiC w osnowie napoin kompozytowych zastosowano analizę fraktalną. Kompozytowe napoiny Ni-TiC formowały się poprawnie, gdy natężenie prądu łuku głównego wynosiło co najmniej 80 A. Warstwy uzyskane dla niższych wartości natężenia prądu nie wykazywały metalurgicznego połączenia ze stalowym podłożem, a ponadto występowały w nich niezgodności spawalnicze w postaci dużych pęcherzy gazowych. Badania metalograficzne ujawniły obecność dużych i małych cząstek TiC w niklowej osnowie. Wraz ze wzrostem natężenia prądu liczba małych cząstek wzrastała. Było to powodowane rozpadem dużych cząstek TiC pod wpływem oddziaływania ciekłej osnowy w trakcie napawania. Udział metalu podłoża w napoinie zwiększa się wraz ze wzrostem natężenia prądu, ponieważ zwiększa się także energia liniowa procesu. Również udział objętościowy cząstek TiC w osnowie rośnie, gdy zwiększa się prąd napawania. Dla badanych powłok określono liniowy wymiar fraktalny, stosując zmodyfikowaną metodę box counting dimension (BCD).

Słowa kluczowe: **powłoki kompozytowe Ni-TiC, napawanie plazmowe proszkowe (PPTAW), analiza fraktalna**

INTRODUCTION

Metal matrix composites (MMC) are known for their hardness and exceptional wear resistance. These materials have found use in applications where a high durability to weight ratio, high wear resistance and dimensional stability are the main engineering considerations. Metal matrix composite coatings are deposited on a substrate by three conventional techniques such as laser cladding, thermal spraying and plasma transferred arc [1].

Plasma Powder Transferred Arc Welding (PPTAW) is one of the methods frequently used in surface modification or in regeneration in the machine part industry. The main advantages of this method are high temperature plasma arc, excellent arc stability and high deposition rate. Due to the high energy of a concentrated plasma arc, the substrate material melts at a low depth, solidifies rapidly and in result a fine structure of coatings is obtained, a low heat affected zone and low dilution are present as well. The coatings obtained at optimal parameters are characterized by a low dilution coefficient in the range of 5÷10% [2, 3].

Nickel base alloys are often used as the matrix of composite coatings deposited by the plasma transferred arc method. Nickel base alloy coatings have a good surface finish, high wear resistance and corrosion resistance also at elevated temperatures [4-6]. Moreover, reinforcement of these coatings may be obtained through the addition of hard particles, for example the carbides of transition metals from IVB, VB and VIB of the periodic table [7-10]. These carbides have a high melting point, high hardness and thermodynamic stability [11].

Composite coatings possess optimum high properties when distribution of the reinforcing phase is uniform in the matrix. However, there is a number of factors which influence this distribution and also the formation of composite coatings by PPTAW. The most important of them is the type and intensity of mutual interaction between the reinforced particles and liquid matrix.

In this paper, the microstructures of nickel base composite coatings reinforced by titanium carbide are presented. The distribution of TiC particles in the nickel matrix as a function of the welding current was characterized by fractal analysis. The dilution coefficient of the coatings and volume content of carbides were also calculated.

EXPERIMENTAL PROCEDURE

Sample preparation

The PTA process was performed using a PTA 301 Control M machine (Hettiger Stellite GmbH). The PTA surfacing parameters are listed in Table 1. The welding current was altered within the range of 60÷120 A. The other parameters remained constant.

TABLE 1. **Experimental parameters for PPTAW process**
TABELA 1. **Parametry procesu napawania PPTAW**

Parameter	Units	Value
Welding current	[A]	60, 70, 80, 90, 100, 110, 120
Powder feed rate	[g/min]	6, 10
Welding speed	[mm/min]	50
Pilot current	[A]	40
Voltage	[V]	25
Flow Gases:		
plasma (argon)	[l/min]	1.5
shield (argon)	[l/min]	8
powder transport (argon)	[l/min]	5
Oscillation axis	[mm]	8
Distance between torch and substrate	[mm]	15
Oscillation axis speed	[mm/min]	450
Torch gap	[mm]	4

A blend of nickel alloy powder DA 22 produced by Deloro Alloy Inc., whose chemical composition is 0.03 C, 2.4 Si, 1.4 B, 0.4 Fe, rest Ni, with 40 vol.% TiC was selected as the precursor material for fabricating Ni-TiC composite coatings. The nickel alloy powder was regular in shape whereas the TiC particles were irregular. The powder particles sizes were in the range of 45÷150 μm.

Nickel base alloy composite coatings reinforced by hard titanium carbide particles were deposited by the PPTAW method onto low alloy steel S355J0 according to the European Norm (EN 10025÷2:2004). The substrate steel plate 10x50x150 mm was cut and then sandblast cleaned and finally rinsed with ethyl alcohol just before the surfacing process.

Coating tests

The deposited composite coatings for metallographic examination were first cut perpendicular to the surface layer at the same distance 20 mm from the toe of the overlay in order to have comparable conditions for testing. Due to the high hardness of the deposited coatings, an electrodischarge cutting machine was employed. The cross-section of the samples was prepared according to standard procedure (grinding, polishing, etching). Then the microstructures of the coatings were studied by optical microscope.

The volume fraction of the reinforced titanium carbide phase was calculated for each sample with the MultiScanBase computer program. Dilution coefficient *D*, defined as the ratio of field *P* of the partially melted substrate to the summarized field of *P* and the field of deposited layer *S*, was calculated according to formula:

$$D = \frac{P}{P+S} \cdot 100\% \tag{1}$$

The distribution of TiC in the nickel alloy matrix was evaluated with the use of fractal analysis. In order to do this, a special computer program was written by the Department of Welding Engineering at Warsaw University of Technology. The one dimensional line-counting algorithm has been used to obtain the fractal dimension of the analyzed structures [12].

RESULTS

The metallographic examination revealed that coatings obtained with in the range of 60÷80 A welding current have discontinuities in the interface layer - substrate and a number of large air bubbles. Moreover, the overlay obtained by using 60 and 70 A welding current has a very irregular surface (Fig. 1) therefore the research of it was given up.

The composite coatings obtained with a higher than 80 A welding current were correctly formed. The structure of the nickel alloy - titanium carbide composite coatings is presented in Figure 2. No cracks or continuous bonding between the layer and substrate are observed. However, small pores at the top of the layer on the interface matrix - reinforced phase are present. Segregation of the reinforcing phase in the nickel alloy can be seen clearly. Large TiC particles are located at the top of the coating, whereas small particles are uniformly distributed in the matrix.

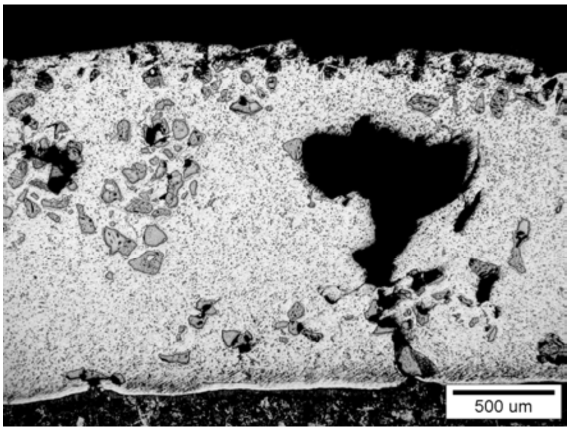

Fig. 1. Typical defects of composite coatings obtained by welding current 70 A

Rys. 1. Typowe wady kompozytowych powłok otrzymanych przy natężeniu prądu napawania 70 A

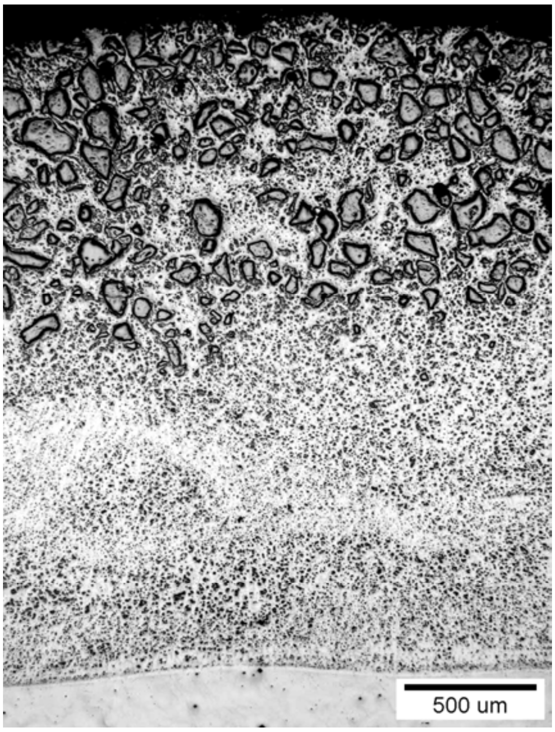

Fig. 2. Cross-section of composite coatings deposited by welding current 100 A

Rys. 2. Przekrój poprzeczny kompozytowej powłoki uzyskanej przy prądzie napawania 100 A

In Figure 3 the morphology of titanium carbide in the matrix is presented. One can see both large and small irregular particles in the nickel alloy. The amount of small particles of TiC increased when the welding current increased. As a result of the interaction between the nickel alloy matrix and high energy plasma arc with titanium carbide during the surfacing process, small particles are formed. Figure 4 demonstrates TiC particle disintegration. It is seen that small particles are formed out of large TiC particles when they separate from the surface. The decomposition of large TiC particles is also caused by nickel alloy penetration.

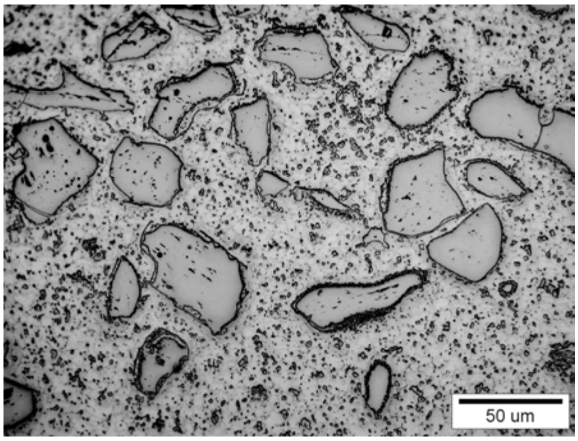

Fig. 3. Structure of nickel alloy - titanium carbide composite coatings

Rys. 3. Struktura kompozytowej powłoki stop niklu - węglik tytanu

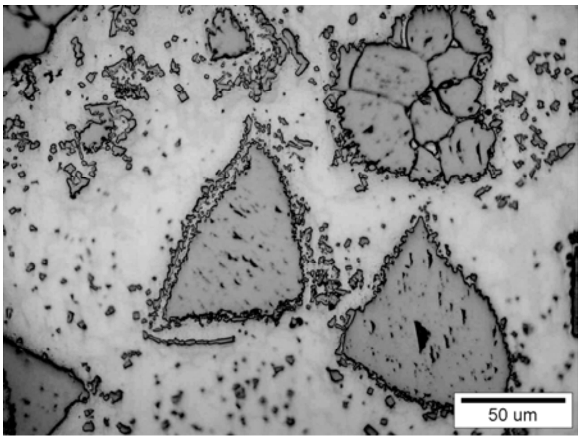

Fig. 4. Disintegration of TiC in nickel matrix

Rys. 4. Dezintegracja TiC w niklowej osnowie

Figure 5 shows the dilution coefficient of the composite coatings as a welding current function. Moreover, Figure 6 presents the influence of welding current on the volume fraction of titanium carbide in the nickel alloy matrix. It is seen that both the dilution coefficient and volume fraction of TiC increase with an increase in welding current.

Selected cross-sections of the coating structures were subjected to fractal analysis. Computer image processing techniques were applied to prepare the structures for measurements. An example binary image is shown in Figure 7. The results of fractal dimension (D_I) measurements are collected in Table 2. To demonstrate the character of the fractal dimension for coating cross-sections, it has been plotted in Figure 8 against the image width.

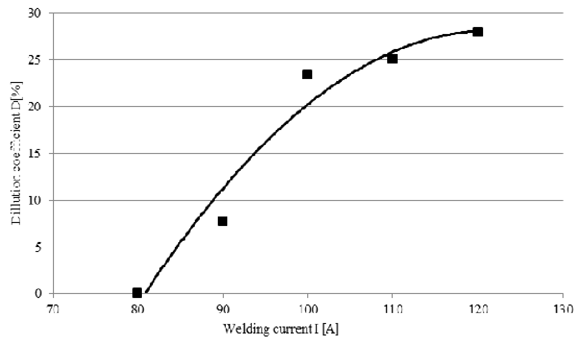

Fig. 5. Calculated dilution coefficient D of deposited coatings as function of welding current

Rys. 5. Zależność udziału metalu podłoża w napoinie D w funkcji natężenia prądu napawania

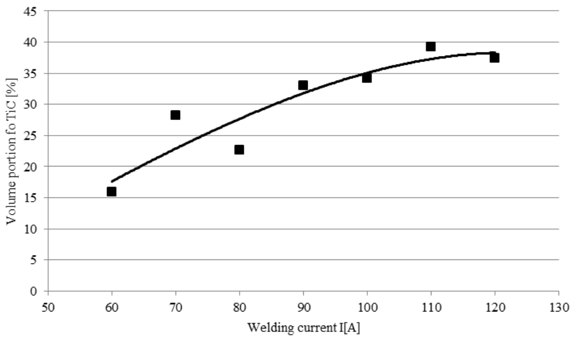

Fig. 6. Volume portion of reinforced phase in composite coatings

Rys. 6. Objętościowy udział fazy umacniającej w kompozytowych napoinach

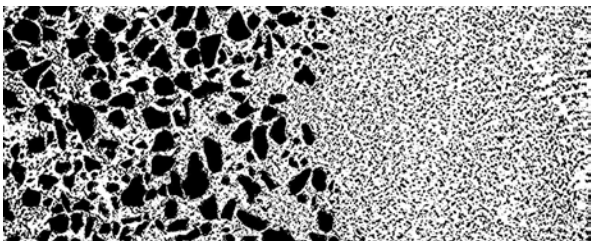

Fig. 7. Binary image of investigated coating (I = 120 A - TiC - black pixels)

Rys. 7. Obraz binarny powłoki (I = 120 A – TiC - czarne piksele)

TABLE 2. **Fractal dimension of analyzed coatings**
TABELA 2. **Wymiar fraktalny badanych powłok**

Welding current [A]	Fractal dimension						
	D_{lmin}	D_{lmean}	D_{lmax}	R	Var	S	CV [%]
60	0.4670	**0.7789**	0.9453	0.4783	0.0099	0.0997	12.80
70	0.7544	**0.8395**	0.9145	0.1601	0.0006	0.0299	3.57
80	0.7220	**0.8229**	0.9536	0.2316	0.0027	0.0524	6.37
90	0.7660	**0.8575**	0.9420	0.1760	0.0016	0.0409	4.77
100	0.7445	**0.8482**	0.9544	0.2099	0.0021	0.0465	5.49
110	0.6840	**0.8462**	0.9614	0.2774	0.0045	0.0676	7.99
120	0.6601	**0.8296**	0.9474	0.2873	0.0050	0.0707	8.52
D_{lmin} - minimum value D_{lmean} - mean value D_{lmax} - maximum value				R - range of data set Var - variance S - standard deviation CV - coefficient of variation			

According to the rule of fractal dimension measurement, its value should correlate with the TiC content. Therefore, the TiC content was estimated for each measurement line used for calculating the fractal dimension. The changes in TiC content in the coating cross-section deposited at I = 120 A are shown in Figure 9. Comparing the results presented in Figures 8 and 9, we may find similarities in these profiles. The effect of TiC content in the investigated coatings on the fractal dimension is presented in Figure 10. Figure 11 shows the histograms of the fractal dimension data set for coatings deposited at I = 70 A and I = 120 A.

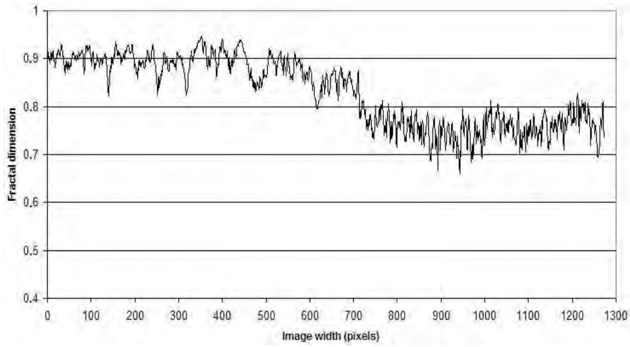

Fig. 8. Fractal dimension of Ni-TiC coatings (I = 120 A)

Rys. 8. Wymiar fraktalny powłoki Ni-TiC (I = 120 A)

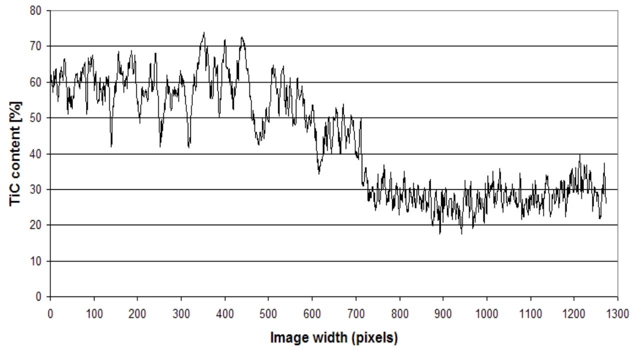

Fig. 9. Distribution of TiC in coating cross-section (I = 120 A)

Rys. 9. Zmiany zawartości TiC na przekroju powłoki (I = 120 A)

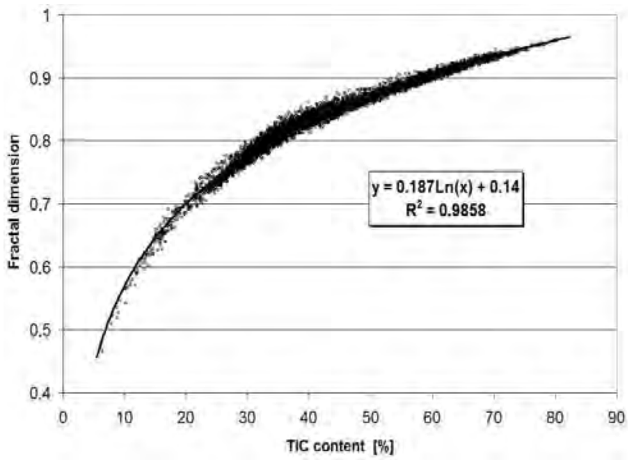

Fig. 10. Fractal dimension of investigated coatings against TiC content

Rys. 10. Wymiar fraktalny badanych powłok w funkcji zawartości TiC

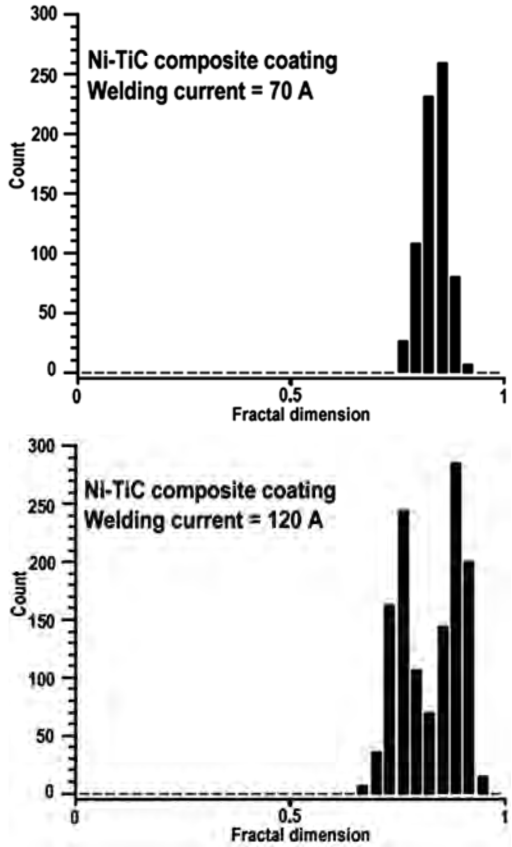

Fig. 11. Histograms of fractal dimension data set (I = 70 A and I = 120 A)
Rys. 11. Histogramy wymiaru fraktalnego (I = 70 A and I = 120 A)

DISCUSSION OF RESULTS

The composite Ni alloy - TiC coatings were correctly formed when the welding current was higher than 80 A. When the energy of the plasma arc is not high enough, the substrate material is melted to a low depth, so it is possible that discontinuities on the boundary layer - substrate will be present (Fig. 1). Moreover, TiC wettability by the liquid nickel alloy is not sufficient in these conditions, which causes big bubbles to form. However, an increase in welding current causes temperature growth of the melting pool therefore, TiC particle wettability by the liquid matrix is higher. In this way a correct overlay is formed.

The microstructure of the composite coatings contains large and small irregular titanium carbide particles (Fig. 4). Small particles of titanium carbide were formed as a result of the disintegration of large TiC particles by high energy plasma arc and interaction with the liquid nickel alloy.

Due to a higher heat energy plasma arc, the substrate material is melted in depth so the dilution coefficient increases (Fig. 5). Moreover, the increase in welding current caused the volume content of the titanium carbide in the matrix to also increase (Fig. 6). Composite coatings obtained by a welding current higher than 100 A have a volume content of TiC similar to the content with the initial powder blend. The increase in welding current through the thermal activity of the wettability process causes a larger amount of reinforcing phase particles to stay in the nickel matrix.

The results of the fractal dimension measurements show that the minimum value of the range of data set (R) is obtained for coating structures deposited at I = 70 A and I = 90 A (0.1601 and 0.1760 respectively). The maximum value (0.4783) has been obtained for the coating structure deposited at current I = 60 A. The larger the difference between the minimum and maximum values of fractal dimension indicates the more complex structure of the coating, with varying TiC distribution. The highest (0.8575) and the lowest (0.7789) mean fractal dimensions values have been reported for coating structures deposited at I = 90A and I=60A respectively. The difference between the highest and lowest mean value (0.0786) is relatively small. Greater values of fractal dimension correspond to a greater TiC content in the coating structure. The character of the curves indicates the existence of two zones of fractal dimension changes (Fig. 8), which correspond to the coating structure (Fig. 7). The both unimodal (I = 70 A, I = 90 A) and bimodal histograms (for the other current values) have been obtained. The lowest variation coefficients have been reported for the coatings deposited at I = 70 A and I = 90 A (3.57 and 4.77% respectively).

CONCLUSIONS

The obtained results allowed the authors to draw the following conclusions:

- The surfacing of composite layers should be carried out at a sufficiently high current due to the presence of high-melting TiC particles. Coatings surfaced with insufficient heat input showed no metallurgical bonding with the base material. Furthermore, the layers revealed a number of imperfections.
- The titanium carbide found in the produced coatings, existed in the form of large, irregular particles but also substantially smaller particles comparing to the initial feedstock material. This was a result of the disintegration of large TiC particles during interaction with the liquid Ni matrix. The process was intensified by an increase in the welding current.
- The higher the welding current, the higher the TiC volume fraction in the matrix despite the increase in partially melted substrate. This was due to thermal activation of the wettability process of TiC by the liquid matrix.
- The results of the present study suggest that fractal dimension analysis may be a suitable tool for structure investigation. Further study in this direction is now in progress.

Acknowledgements

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