PREPARATION AND BASIC CHARACTERISTICS OF NICKEL MATRIX COMPOSITE

Adam NOVOTNÝ, Pavel ROHAN, Jakub KARMÁČEK, Miroslav SAHUL, Marie KOLAŘÍKOVÁ

CTU–Czech Technical University in Prague, Department of Manufacturing Technology, Prague, Czech Republic, EU, Adam.Novotny@fs.cvut.cz

https://doi.org/10.37904/metal.2024.4968

Abstract

Plasma transfer arc surfacing is very perspective technology, which is currently used to create layers with special properties such as corrosion resistance, wear resistance or resistance against high temperatures. In case of Nickel based alloys, it is possible to increase hardness and wear resistance using heat treatment, but it is very expensive and time consuming and impossible to apply on different materials (Nickel based coating and alloy steel base material). Perspective way of increasing wear resistance of Nickel based coatings is combining it with hard ceramic particles using plasma transfer arc surfacing technology. This study deals with creating and characterization of metal matrix composite based on Nickel 625 type alloy with B_4C. Metal matrix composite (MMC) with B_4C was created by co-feeding Nibasit 625 – P/LFe® and B_4C powder into a melting pool. The two powders were mixed together in two ratios. B_4C particles have been dispersed in deposited coatings, they have partially dissolved in Ni-based matrix and formed different microstructural formations such as carbides and borides. Dissolution of B_4C particles ensures good cohesion with matrix. Coatings are well metallurgically connected to the substrate – AISI 304 corrosion resistant steel. Coatings were examined in terms of microstructure. In macro-view perspective Vickers hardness has been measured and abrasion resistance test using dry sand/rubber wheel according to ASTM G65 standard has been performed.

Keywords: Plasma transfer arc surfacing, metal matrix composite, nickel alloys, boron carbide

1. INTRODUCTION

Mechanical wear is one of the most common causes of destruction of machine components. It affects the lifetime of components in many ways: reduction of bearing cross-section, change of the functional dimensions, increasing of coefficient of friction and initialization of fatigue cracks. Because of these reasons, increasing of wear resistance of mechanical components is very important task [1]. Plasma transfer arc (PTA) surfacing is one of the technologies used to change surface properties of machine components [2]. In comparison with other hardfacing technologies, deposits made by PTA surfacing have very low dilution rate (usually under 10%) [3]. Powder allows to create composite materials using combination of metal and ceramic materials. These metal matrix composites can reach very specific properties thanks to possibility of combining different matrix and ceramics and their various ratios [4]. For applications where components are exposed to high temperatures, nickel alloys are often used [5]. Most common way of increasing tensile strength and hardness of some nickel alloys is precipitation hardening [6]. This process however consumes high amount of energy and is impossible to use on just coatings. Combination of nickel alloy matrix and specific ceramic particles can provide similar properties such as precipitation hardening process. 625 type nickel alloy is commonly used in applications where heat and corrosion resistances are needed such as aircraft engines, chemical industry, seawater components and many others. It has high density (8.44 $g \cdot cm^{-3}$) and melting point 1350 °C [7]. To reinforce 625 type nickel alloy various oxide and non-oxide ceramics can be used. Non-oxide ceramics are suitable for their high hardness and heat resistance. Boron carbide is third hardest material known behind diamond and cubic boron nitride and is suitable for reinforcing 625 type nickel alloy. B_4C has low density (2.52 $g \cdot cm^{-3}$) and high melting point (2350 °C), it is also chemically stable even at high temperatures [8]. In order to create compact MMC deposit of required quality the reinforcement particles must not completely dissolve in the matrix, but they must also be bonded strongly enough in the matrix [9]. There are a lot of research possibilities in MMC area, and many scientists are dealing with different metal-ceramics combinations. Rohan et. al. [10] dealt with combination of B_4C and Titanium alloy matrix and his multi-layer deposits showed high abrasion resistance in tribological test. A. Rokanopoulou [11] found very low friction coefficient (0.15-0.30) against Al_2O_3 counterpart of duplex stainless steel MMC with TiC as a reinforcing particles. Sundaramoorthy [12] investigated microstructure, abrasive wear resistance and impact wear resistance of Ni-WC MMC and found that type of tungsten carbide is the most important for wear resistance (deposits with macro-WC shown higher abrasion resistance than with cast-WC).

2. EXPERIMENTAL

Nickel alloy used in this experiment (Nibasit 625 – P/LFe® DEW, Germany) had chemical composition Cr 20.9%, Mo 8.9%, Fe 0.5%, Nb 3.2%, Si 0.5%, Mn 0.2%, Co ≤0.1%, C ≤0.03% (in wt%) and the rest was Ni. The powder had spherical shape and 63-200 μm grain size created by atomization in argon atmosphere. Boron carbide powder had grain size 67-168 μm with sharp edge shape. The MMC coatings were deposited by plasma hardfacing automate PPC 250 R6 (KSK, Ltd., Czech Republic – **Figure 1**) which can work with maximum current 250 A. For specimens with 0 and 15 vol% B_4C in coatings was used pulsation between 50 and 120 A and linear speed 0.38 $mm \cdot s^{-1}$. In case of coatings with 30 wt% B_4C it was necessary to change surfacing parameters to pulsation between 50 and 140 A and increase linear speed to 0.58 $mm \cdot s^{-1}$ in order to achieve stabile process. Oscillation speed 22.4 $mm \cdot s^{-1}$ and oscillation width 28 mm were the same for all specimens. Feeding rate of the powder was set to 18.2 $g \cdot min^{-1}$. Powders were mixed in self-made mixer before entering the torch. Plasma and feeding gas were Ar with 30 vol% of He, as shielding gas was used argon 4.8.

Figure 1 Plasma hardfacing automate PPC 250 R6, KSK, Ltd.

Microstructure of the coatings was examined using light (Zeiss Neophot 21) microscopy. Samples were cut by metallographic saw, grinded, polished and etched. Hardness test was performed on BuehlerIndetaMET 1104 tester according to Vickers with load of 9.81 N (HV1). On each sample was measured 15 values of hardness from substrate through interface with deposit, deposit itself and surface of the deposit. In order to establish abrasion resistance of deposits the test according to standard ASTM G65 for measuring abrasion using the dry sand/rubber wheel apparatus was performed using in house build testing device. Samples were grinded to flatten the surface. With every sample has been tested also test specimen to make sure that the results of the test are valid. Samples were pushed against rubber wheel with diameter 240 mm using pressure of 130 N. As abrasive material has been used SiO_2 sand with grain size 200-500 µm and mass flow of 310 g·min^{-1}. The wheel spins at 950 rpm. The test lasts 6 min 12 s while the wheel covers the distance of 1 km. Results of the abrasion resistance test are weight loss. Weight loss was measured using laboratory scales Sartorius PCB2000.

3. RESULTS AND DISCUSSION

On images of macrostructure (**Figure 2**), there is to be seen not homogenous distribution of B_4C particles in deposit with 15 vol% B_4C. In deposit with 30 vol% B_4C the distribution of particles is more homogenous. B_4C has almost three times lower density than Ni-based alloy 625 type, which causes B_4C particles to float up the melted metal to the surface. To eliminate this effect, it is necessary to keep the melt pool as small as possible. The samples with 30 vol% B_4C were deposited with higher depositing speed so the metallurgical bond with substrate is worse than on the samples with 15 vol% B_4C, but distribution of particles is more homogenous. Original B_4C particles have sharp edge shape, but particles observed in deposits on images of microstructure have more rounded shape. It is caused by dissolution of these particles in Nickel-based matrix.

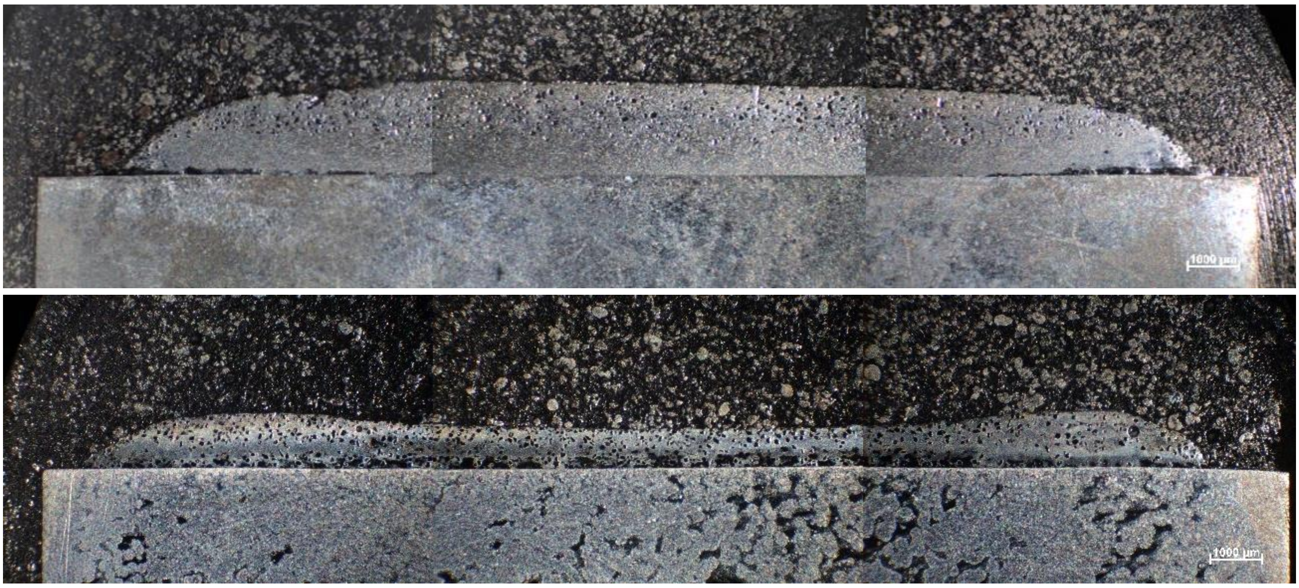

Figure 2 Macrostructure of MMC deposits (15 vol% B_4C up, 30 vol% B_4C down)

On the images of microstructure from light microscopy (**Figure 3**), there is visible dissolution of B_4C particles. This is less significant in deposit with 30 vol% B_4C, particles are larger and have also sharper edges, which is caused by different depositing parameters. In the structure there are also precipitates formed by reaction of dissolved B_4C particles with Nibasit 625 – P/LFe® matrix. There is high number of fine precipitates in the deposit with 30 vol% B_4C. In the deposit with 15 vol% B_4C the precipitates are larger and there is less of them. It is caused by higher temperature of deposit with 15 vol% B_4C (the highest temperature measured by thermocouples was almost 1000 °C compared to deposit with 30 vol% B_4C where the highest temperature was around 850 °C) so the diffusion processes lasted longer and were more intensive.

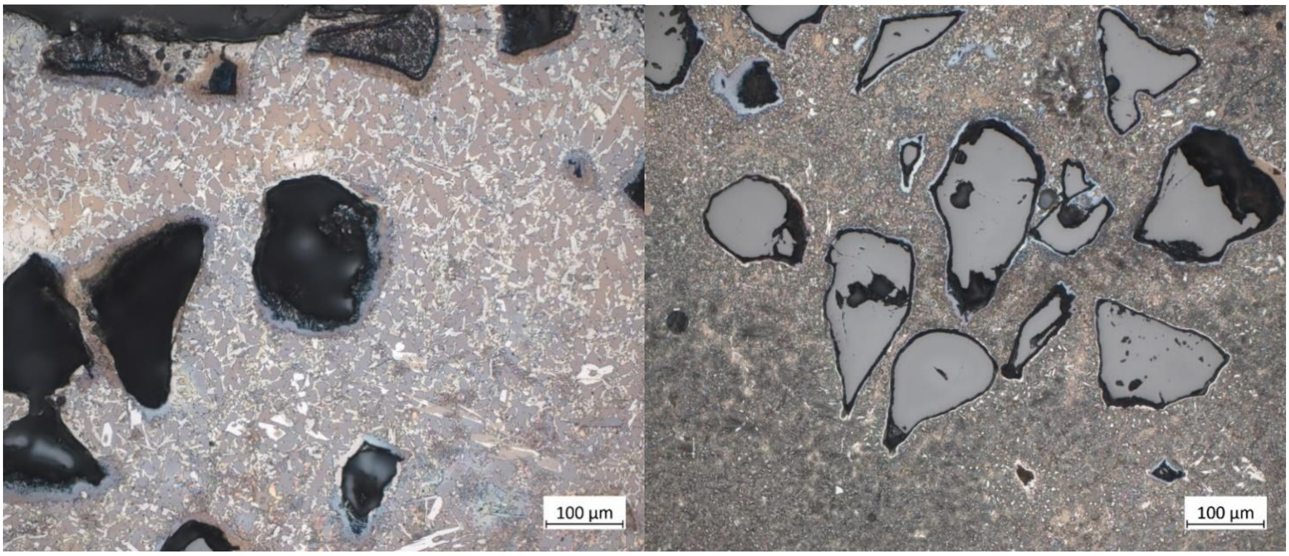

Figure 3 Microstructure of MMC deposits, LM 200x (15 vol% B_4C left, 30 vol% B_4C right)

Most common property measured on functional surfaces is their hardness. In this study was used measurement method according to Vickers. In general, hardness is the highest near deposits surface. It is caused by higher concentration of B_4C particles and connected carbides and borides. It has been proven that the higher the concentration of B_4C in additional material, the higher the hardness of deposits is. Average hardness of composite deposits 0.1 mm under the surface is 1047 HV1 (deposit with 30 vol% B_4C), 824 HV1 (deposit with 15 vol% B_4C) respectively. For comparison, average hardness of deposit with 100% Nibasit 625 – P/LFe® is 214 HV1 (**Table 1**).

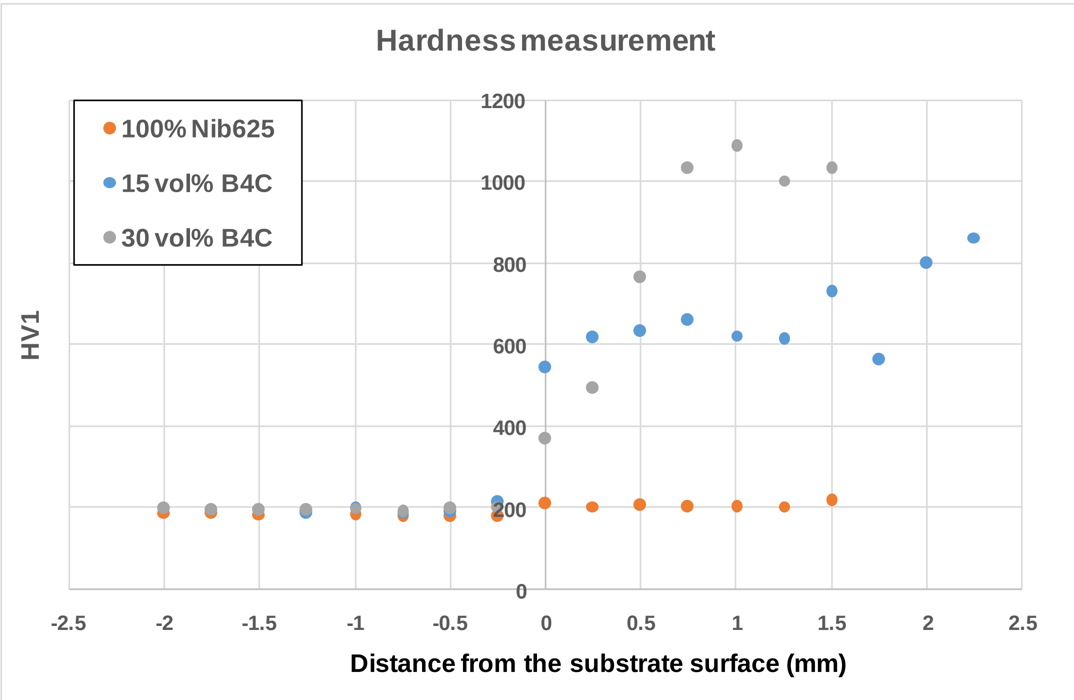

Figure 4 Hardness throughout the MMC deposits (mm)

Hardness of deposit with 15 vol% B_4C is slowly rising from 550 HV1 to over 800 HV1. In case of deposit with 30 vol% B_4C is the increase much steeper, but hardness near interface of deposit and substrate is just 385 HV1 (**Figure 4**). This deposit acts as functionally graded material.

Table 1 Hardness 0.1 mm under deposits surface measured in HV1

Measurement	100% Nib625	Nib625+15% B_4C	Nib625+30% B_4C
1	217.7	862.2	1031.5
2	227.7	755.3	1032.7
3	200.2	839.5	1049.4
4	215.6	778.7	1093.4
5	209	887.9	1030.9
Average	214	824	1047

Weight loss of both composite samples after abrasion resistance test was very similar, sample with 15 vol% B_4C lost 0.102 g and sample with 30 vol% B_4C lost 0.089 g (which is difference 14.6%). For comparison weight loss of sample with 100% Nibasit 625 – P/LFe® was 0.243 g. On the macroscopic images of worn-out surface of composite deposits there are visible B_4C particles (**Figure 5**). It shows that these particles are very well connected with Nibasit 625 – P/LFe® matrix.

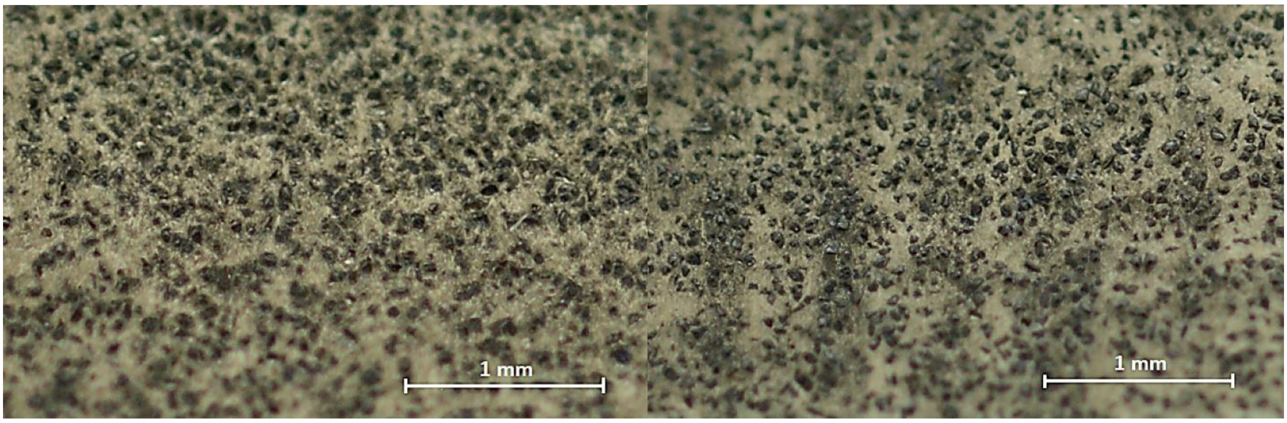

Figure 5 Surfaces after abrasion resistance test (15 vol% B_4C left, 30 vol% B_4C right)

4. CONCLUSION

In this study, nickel-based metal matrix composites with 0, 15 and 30 vol% B_4C have been deposited by plasma transfer arc surfacing on the corrosion resistant steel AISI 304 substrate. The deposits are metallurgically bonded to the substrate and don´t contain porosity or macroscopic cracks. Distribution of B_4C particles is relatively homogenous. Deposits are affected by two different reinforcement effects – by embedded particles of B_4C and by microstructural particles formed by dissolution of B_4C particles and its reaction with Ni-based alloy. Hardness testing showed 4-5 times increased hardness of MMC deposits in comparison with deposit with 0 % B_4C. The deposit with 30 vol% B_4C acted as functionally graded material with hardness decreasing from free surface towards substrate. Performed test of abrasion wear resistance proved significantly increased wear resistance of composite deposits.

ACKNOWLEDGEMENTS

The research was supported by Department of Manufacturing Technology at the Faculty of Mechanical Engineering, which belong to the Czech Technical University in Prague.

This work was supported by the VEGA grant agency of The Ministry of Education, Research, Development and Youth of the Slovak Republic, and Slovak Academy of Sciences, project No. 1/0287/21.

REFERENCES

[1] WENZHENG, Zhai a LICHUN, Bai Recent progress on wear-resistant materials: Designs, properties, and applications. *Advanced Science*. 2021, vol. 8, no. 11, pp. 1-29 [cit. 2024-05-13]. Viewed from doi: https://doi.org/10.1002/advs.202003739.

[2] SIDOROV, S.A., KHOROSHENKOV, V.K., LOBACHEVSKII, Ya.P., AKHMEDOVA, T.Sh. Improving wear resistance of agricultural machine components by applying hard-alloy thick-layer coatings using plasma surfacing. *Metallurgist*. 2017, vol. 60, pp. 1290–1294 [cit. 2024-05-13]. Viewed from doi: https://doi.org/10.1007/s11015-017-0443-7.

[3] LAKSHMINARAYANAN, A. K., BALASUBRAMANIAN, V., VARAHAMOORTHY, R., BABU, S. Predicting the dilution of plasma transferred arc hardfacing of stellite on carbon steel using response surface methodology pp. 779-789 [cit. 2024-05-15]. Viewed from doi:10.3365/met.mat.2008.12.779.

[4] DEUIS, R.L., YELLUP, J.M., SUBRAMANIAN, C. Metal-matrix composite coatings by PTA surfacing. *Composites Science and Technology*. 1998, vol. 58, no. 2, pp. 299-309 [cit. 2024-05-13]. Viewed from doi: https://doi.org/10.1016/S0266-3538(97)00131-0.

[5] CZUPRYŃSKI, A., WYGLĘDACZ, B. Comparative analysis of laser and plasma surfacing by nickel-based superalloy of heat resistant steel. *Materials*. 2020, vol. 13, no. 10, p. 2367 [cit. 2024-05-13]. Viewed from doi: https://doi.org/10.3390/ma13102367.

[6] SUKUMARAN, A., GUPTA, R.K., KUMAR, V.A. Effect of heat treatment parameters on the microstructure and properties of inconel-625 superalloy. *Journal of Materials Engineering and Performance*. 2017, vol. 26, pp. 3048–3057 [cit. 2024-05-13]. Viewed from doi: https://doi.org/10.1007/s11665-017-2774-8.

[7] SHANKAR, V., SANKARA RAO, K.B., MANNAN, S.L. Microstructure and mechanical properties of Inconel 625 superalloy. *Journal of Nuclear Materials*. 2001, vol. 288, no. 2-3, pp. 222-232 [cit. 2024-05-13].]. Viewed from doi: https://doi.org/10.1016/S0022-3115(00)00723-6.

[8] DOMNICH, V., REYNAUD, S., HABER, R.A., CHHOWALLA, M. Boron carbide: Structure, properties, and stability under stress. *Journal of the American Ceramic Society*. 2011, vol. 94, no. 11, pp. 3605-3628 [cit. 2024-05-13].]. Viewed from doi: https://doi.org/10.1111/j.1551-2916.2011.04865.x.

[9] WANG, Xibao. The metallurgical behavior of B_4C in the iron-based surfacing alloy during PTA powder surfacing. *Applied Surface Science*. 2005, 252(5), 2021-2028 [cit. 2024-05-13]. Viewed from doi: https://doi.org/10.1016/j.apsusc.2005.03.171.

[10] ROHAN, P., LUKÁČ, F., KOLAŘÍKOVÁ, M. Pulsed plasma surfacing of titanium matrix cermet based on B_4C. *Journal of Thermal Spray Technology*. 2022, vol. 31, pp. 1975–1984. [cit. 2024-05-13]. Viewed from: https://doi.org/https://doi.org/10.1007/s11666-022-01421-0.

[11] ROKANOPOULOU, A. PAPADIMITRIOU, G.D. Titanium carbide/duplex stainless steel (DSS) metal matrix composite coatings prepared by the plasma transferred arc (PTA) technique: microstructure and wear properties. *Journal of Coatings Technology and Research*. 2010, vol. 8, pp. 427–437. [cit. 2024-05-15]. Viewed from: https://doi.org/https://doi.org/10.1007/s11998-010-9283-0.

[12] SUNDARAMOORTHY, R., TONG, S.X., PAREKH, D. Effect of matrix chemistry and WC types on the performance of Ni-WC based MMC overlays deposited by plasma transferred arc (PTA) welding. *Wear*. 2017, no. 376-377, pp. 1720-1727. Viewed from: https://doi.org/https://doi.org/10.1016/j.wear.2017.01.027.