598. The influence of mechanical vibrations on properties of Ni-based coatings

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Abstract. This article reports on research work that was undertaken on Ni-based thermally-sprayed and fused coating deposited on steel substrate. Mechanical vibrations were introduced during fusing process and the impact of vibrations on the properties and microstructure of coatings was investigated. Microstructures of sprayed and sprayed–fused coatings were compared including evaluation of porosity. The microstructure of sprayed coating consists of partly melted and unmelted particles. A lot of voids are present between the splats. The as-sprayed coating is bonded to the substrate mechanically or by adhesion. The porosity was significantly reduced and strong metallurgical bond between the fused coating and substrate was formed after fusing operation. The hardness and microhardness of different zones of coatings as well as wear resistance were assessed.

Keywords: thermal spray, vibration treatment, Ni-based coating.

Introduction

Service life of machine elements largely depends on the behavior of their surface in conditions of wear and corrosion. Thermal spray technology is one of the most effective processes to resist corrosion, oxidation, and wear. It encompasses a family of coating processes that are grouped into three major categories: flame spray, electric arc spray, and plasma arc spray [1, 2]. Some advantages and disadvantages are typical for each category and satisfactory results are not necessarily obtained. The flame-sprayed coatings are characterized by high porosity (10–20%) and poor adherence to the substrate. Despite this fact flame spray remains number one in certain application areas [3]. With purpose to reduce porosity and improve coating adherence to the substrate, flame spray is often combined with successive melting process [4].

Spray materials for flame spray processes are used in the form of wire, rods, or powder. Feedstock in powder form allows more multipurpose and flexible processes. Virtually any material can be used to create coating by flame spray: metals, ceramics, cermets, plastics. Powders of self-fluxing metal alloys have received most common application for spray-fuse processes [5]. In the particular case where wear and corrosion resistance at low and moderate temperature are required, the use of Ni-base self-fluxing alloys (NiCrBSi) has received widespread use [6]. The advantages of Ni-based self-fluxing alloys are especially related to coating large size components such as oil drilling equipment and agricultural machinery, etc. [7].

The remelting of the coating is carried out by heating to a temperature between the solidus and the liquidus [6]. Addition of boron reduces the melting point due to the presence of a eutectic phase, and, as a result, expands solidification interval of the Ni alloys and makes easier spray and remelting processes [4, 8]. At the same time B and Si additions are used as de-oxidizers [6, 8]:

$$(FeCr)_xO_{x+y} + 2B + Si \rightarrow xFe + xCr + B_2O_x \cdot SiO_y$$

The role of Cr is to improve the mechanical and wear properties by reacting with other elements (B, C) and formation of hard precipitates (Cr_7C_3, Cr_3C_2, CrB, $(CrFe)_{23}C_6$) [4, 6, 8]. Fe modifies the diffusion rates [8]. The variation of alloy elements ratio, small addition of other elements (such as Mo, Cu), Ni based powder mixing with hard particles (WC) allows wear, tribological and corrosion properties in a wide range.

The microstructure and properties of sprayed and fused Ni-based self-fluxing coatings are investigated using different thermal spray and fuse procedures, using powders of different chemical composition, modified with different additives and mixed with different sort of hard particles [3, 4, 6-8]. Deoxidation, degasation, diffusion and another processes take place during remelting. The final quality of coatings in large degree depends on the efficiency of remelting process. As far as we know no works are published on NiCrBSi coatings remelted by heating combinated with vibration treatment.

The positive impact of mechanical vibration on the microstructure and properties of materials is well known [9]. The impact of vibration of different frequency (from 20 Hz to ultrasound) on the structure, properties, and stress state of materials is studied using it in different processes, such as casting and welding of metals and alloys, electrodeposition of metal coatings, extrusion of nanocomposites, crystallization of polymer, etc. [10–19]. The most important effects of vibration in point of spray-fuse technology are grain refinement effect, more effective deoxidation, improvement of mechanical and special properties, relieved stress state. The question is whether it is possible to obtain the same effects in thermal spray-fuse technology.

The aim of this research is to investigate influence of vibration treatment on the microstructure and properties of Ni-based coatings deposited by flame spay-fuse technology.

Coating methodology

With purpose to investigate influence of vibration treatment several fusing experiments were carried out. Before fusing self-fluxing Ni based alloy powders (Table 1) were deposited on low carbon hot-rolled steel substrate (100x100x10 mm) by flame spray techniques. The preparation of substrate and spraying were performed according to recommendations of producer of powders and spraying/fusing tools. The main parameters of spraying are listed in Table 2.

Table 1. Chemical composition (in wt. %) of NiCrBSi powder and substrate

Material	Ni	Cr	Fe	B	Si	C	Mn	S	P	N	Cu
Ni alloy	bal	10.2	2.79	1.61	3.19	0.44	-	-	-	-	-
Steel S235J0	-	-	bal	-	-	0.17	1.40	0.030	0.030	0.012	0.55

Table 2. Preparation of substrate and spraying parameters

Preparation of substrate	Cleaning with degreasing agent. Grit blasting	Spraying distance	170 mm
Preheating of substrate	250-290 °C neutral oxy-acetylene flame	Spraying rate/step/passes	250 mm/s / 5 / 8
Spraying flame	neutral oxy-acetylene flame 0.7 bar C_2H_2 / 4 bar O_2	Thickness of as-sprayed layer	1.2-1.4 mm

Sprayed layers were refused by heating up to 1100°C with neutral oxy-acetylene flame. In order to determine a range of significant impact the fusing experiments covered a large range of frequencies. Six series of specimens were fused under vibratory treatment and one series was fused without vibration using standard fusing procedure (Table 3). The mechanical vibrations were introduced perpendicular to the coating surface, during fusing and after fusing till temperature of coating reached 500°C. Robotic equipment was used in order to make the same spraying and fusing conditions for each specimen (Fig. 1.).

Table 3. Vibration treatment parameters

Series	1	2	3	4	5	6	7
Frequency, Hz	20	100	200	1000	2000	10000	No vibration
Amplitude, µm	255	57	52	31	10	<1	

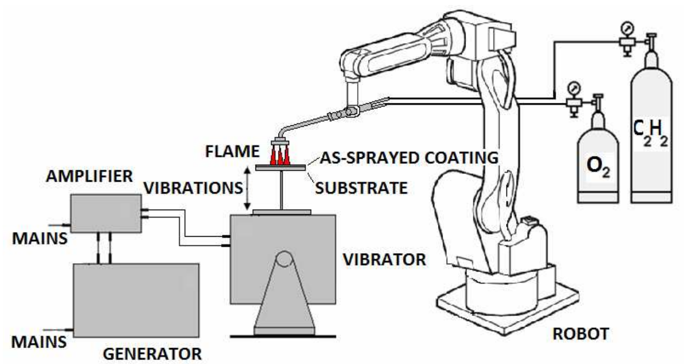


Fig. 1. Scheme of remelting of as-sprayed coatings under vibration treatment

Examination and characterization

Covered samples were sectioned perpendicular to the coating layer, then mounted and polished using conventional metallographic procedures. Microstructures of as-sprayed layers and sprayed-fused layers were observed on the polished and etched transverse cross-sections and on the polished and etched top of coatings using an optical microscope. The last polishing step was carried out using diamond polishing paste with grit size up to 1 µm. The 20 ml HCl / 20 ml H_2O / 4 g $CuSO_4$ solution was used for etching. NiCrBSi powder was mixed with epoxy glue and performed briquette was also polished, etched, and examined with optical microscope.

Determination of porosity (% area) was performed on the basis of optical micrographs using image analyzing software. An X90 magnification was used. Porosity was measured on 20 areas of each specimen and the average values were determined.

Hardness was measured on the grinded and polished top of sprayed-fused coatings using conventional Vickers hardness tester with a 30 kg load. The value presented is the average of 10 measurements after the highest and lowest values being eliminated.

Microhardness test was carried out using conventional Vickers microhardness tester with a 200 g load. Measurements were done on polished transverse cross-sections.

Two-body dry abrasive wear test was carried out using as a counter abrasive SiC grinding paper #220 (grit size of 58 µm) and 35 N load. Each specimen was tested during 16000 revolutions and the data of first 2000 revolutions was disregarded to eliminate roughness effects. The paper was renewed every 2000 revolutions. The thickness of removed layers was controlled by measurement of indentation diameter made before test. The weight of specimens was measured also. Indentations and weight measurements showed the same results.

Results and discussions

The NiCrBSi powder was first examined with optical microscope. Nominally powder consists of fine spherical grains, but really it was found that part of powder particles has the shape of flakes and of coalesced spheres (**Fig. 2, a, b**). Higher magnification showed that particles have the fine crystal structure of primary solidification (**Fig. 2, c**).

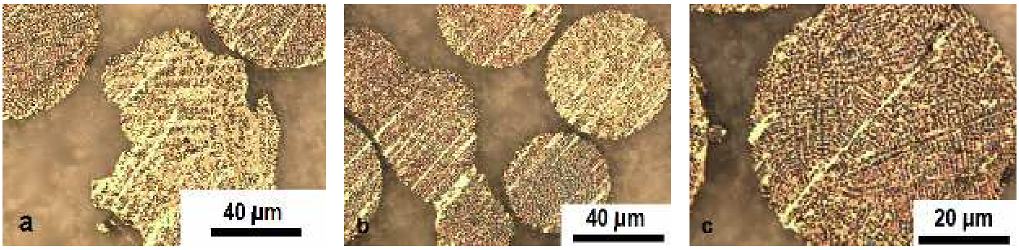


Fig. 2. Optical micrographs of polished and etched (20 ml HCl / 20 ml H_2O / 4 g $CuSO_4$) NiCrBSi powder

The as-sprayed coating exhibit discontinuous microstructure with a lot of unclosed voids and large gaps between the splats. The most of powder is incorporated in coating as separated particles with no changes of their shape. A wide sharp interface zone can be clearly observed on cross-sectional micrographs (**Fig. 3, a; Fig. 4, a**), so as-sprayed coating is bonded to the substrate by poor mechanical adherence only. The block of optical micrographs on **Fig. 5** presents microstructures of coatings after remelting process. The primary boundaries between splats have been liquidated and monolithic structure of Ni solid solution and Ni eutectic can be well distinguished. Strong metallurgical bond exists between substrate and coating (**Fig. 4, b**). The effect of grain refinement was found in all specimens made under vibration.

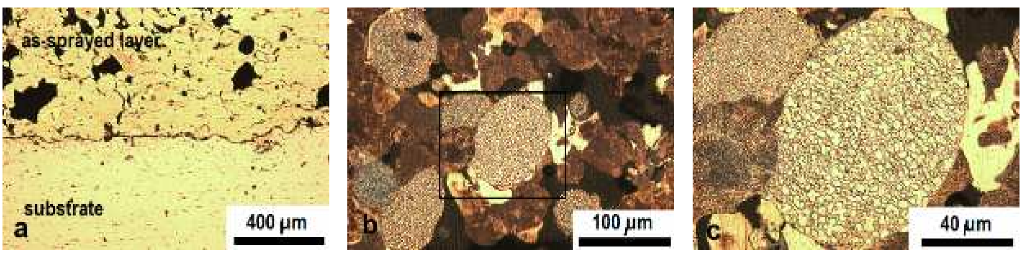


Fig. 3. Optical micrographs of polished cross-sections (a), polished and etched (20 ml HCl / 20 ml H_2O / 4g $CuSO_4$) top of as-sprayed layer (b, c)

The coating thickness was determined after spraying and after fusing on polished transverse cross-sections with optical microscope. The value of thickness of fused coatings was about 1 mm and this is about 20-25 % lower than in the case of as-sprayed coating.

The porosity after conventional fusing was about 5%. Low frequency vibrations of 20 Hz downgrade this result. Application of 200 Hz and higher vibrations reduce porosity to nearly 4 %. The best result (about 3 %) was observed in coating obtained under 100 Hz vibrations (**Fig. 6, a**). Hardness measurements indicate slight increase of hardness with introducing vibrations of

20 Hz frequency in comparison with coating obtained without vibration treatment. Higher hardness was observed in samples remelted under vibration treatment of frequency 100 Hz and above.

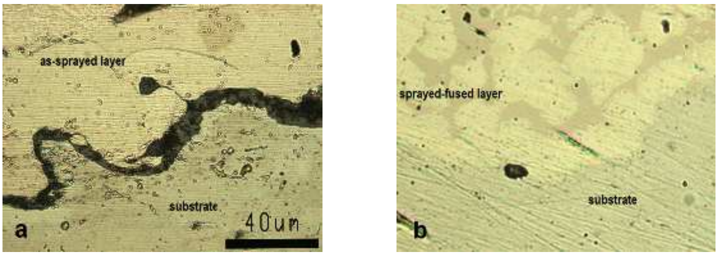


Fig. 4. Cross-sectional optical micrographs of sprayed coatings: before (a) and after fusing (b)

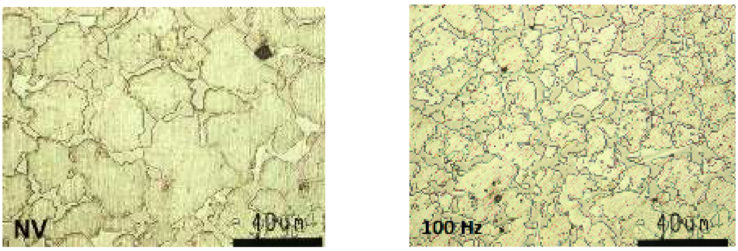
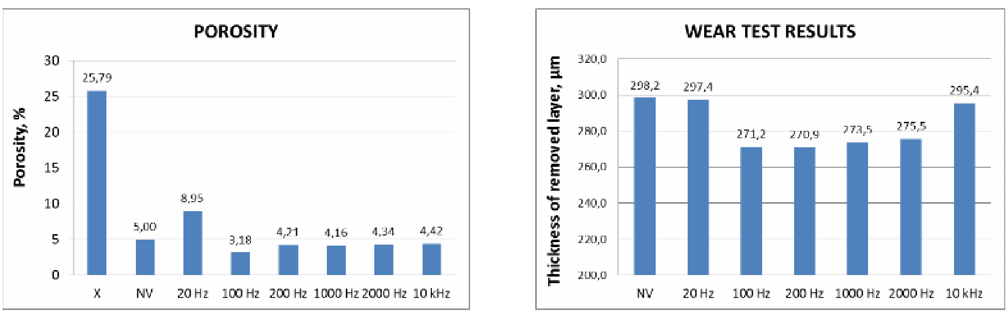


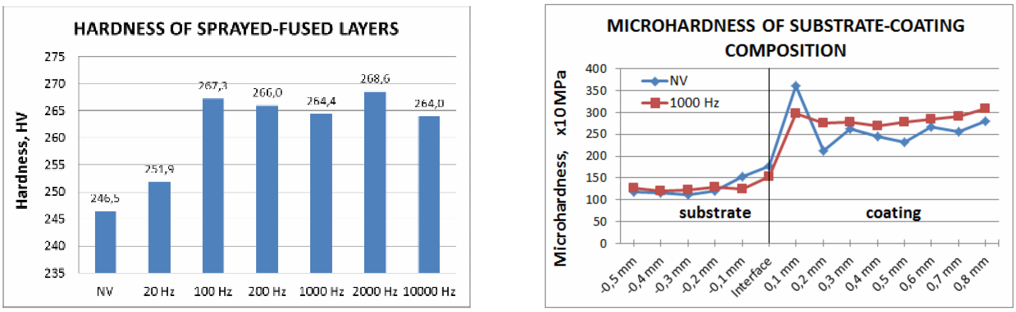
Fig. 5. Optical micrographs of polished and etched (20 ml HCl / 20 ml H_2O / 4g $CuSO_4$) coatings after fusing: NV – no vibration, 100 Hz – vibration treatment condition during fusing

The diagram on Fig. 6 (b) presents wear resistance of coatings. It was established that specimens obtained under 100 and 200 Hz frequency have the best wear resistance. Specimens made under 1000 and 2000 Hz indicated slightly worse result. No appreciable improvment of wear resistance in comparison with unvibrated specimen was determined after testing of specimens under 20 Hz and 10 000 Hz.

Microhardness test revealed that the microhardness of zone located in the middle part of coatings and zone close to surface has a value between 250 and 300. No significant impact of vibration on coatings micro-hardness value was observed. As an example the distributions of microhardness within unvibrated coating and coating made under 1000 Hz are provided (**Fig. 6, d**). Local increase of microhardness near interface was detected in unvibrated coating. It was found that the distribution of microhardness in all coatings obtained under vibration has more uniform character in comparison with unvibrated coating. It was also determined that the substrate microhardness was increased near interface in all specimens. This effect can be related to diffusion process.



a b



c) d)

Fig. 6. Results of evaluation of coating properties: porosity (a), wear (b), hardness (c) microhardness (d)

Conclusions

Several conclusions can be formulated on the obtained results of this research work.

Firstly, it is impossible to produce Ni-based coating with monolithic structure by using only flame spraying. Successive remelting allows reaching this aim. Application of vibration treatment during fusing procedure influences Ni-based coating formation and solidification process. Several observed vibration treatment effects can be noted. The introduction of mechanical vibrations:

- reduces grains size and porosity of sprayed-fused coating;
- slightly increases the hardness of coating;
- improves coating wear resistance.

The impact of mechanical vibrations of different frequency is not same. Particular dependence between tests results and applied vibration frequency was revealed. Low frequency vibrations (20 Hz) increased porosity of fused coating and slightly increased hardness. Wear resistance has remained unchanged. Testing of specimens fused under application of 100 Hz and 200 Hz vibrations demonstrated the most significant positive effect of vibratory action on microstructure and properties.

References

[1] **Joseph R. Davis**. Handbook of thermal spray technology. ASM International, Thermal Spray Society Training Committee. 2004.

[2] **Tobe S.** A review on protection from corrosion, oxidation and hot corrosion by thermal spray coatings. Proceedings ot the 15th International thermal spray conference, 25–29 May 1998, Nice, France. P 3-11.

[3] **Gonzalez R., Garcia M.A., Penuelas I., Cadenas M., del Rocio Fernandez Ma., Hernandez Battez A., Felgueroso D**. Microstructural study of NiCrBSi coatings obtained by different processes. Wear 263, 2007. P 619-624. (www.sciencedirect.com).

[4] **Gomez-del Rio T., Garrido M.A., Fernandez J.E., Cadenas M., Rodriguez J.** Influence of the deposition techniques on the mechanical properties and microstructure of NiCrBSi coatings. Journal of materials processing technology 204, 2008. P 304-312. (www.elsevier.com/locate/jmatprotec).

[5] **Bach F-W., Laarmann A., Wenz T.** Modern surface technology. Weinheim: WILEY-VCH Verlag GmbH and Co. KGaA, 2006.

[6] **Kim H-J., Hwang S-Y., Lee Ch-H., Juvanon P**. Assessment of wear performance of flame sprayed and fused Ni-based coatings. Surface and coating technology 172, 2003. P 262-269. (www.sciencedirect.com).

[7] **Zhang Z., Wang Z., Liang B., Dong H.B., Hainsworth S.V.** Effect of CeO2 on the microstructure and wear behavior of thermal spray welded NiCrWRe coatings. Wear 262, 2007. P 562-567. (www.sciencedirect.com).

[8] **Stoica V., Ahmed R., Itsukaichi T.** Influence of heat-treatment on the sliding wear of thermal spray cermet coatings. Surface and coating technology 199, 2005. P 7-21. (www.sciencedirect.com).

[9] **Abramov O., Chorbenko I., Shvegla Sh.** Ultrazvukovaja obrabotka materialov. Moscow: Mashinostroienie, 1984.

[10] **Wu H., Zhao G., Mu J., Li X., He Y.** Effect of ultrasonic dispersion on structure of electrodeposited Ni coating on AZ91D magnesium alloy. Transaction of nonferrous metals society of China 20, 2010. P 703-707. (www.sciencedirect.com).

[11] **Watanabe T., Shiroki M., Yanagisawa A., Sasaki T.** Improvement of mechanical properties of ferritic stainless steel weld metal by ultrasonic vibration. Journal of materials processing technology 210, 2010. P 1646-1651. (www.elsevier.com/locate/jmatprotec)

[12] **Jurčius A.** Effect of vibratory treatment on residual stresses in structural steel weldments. Summary of doctoral dissertation. Vilnius: Technika, 2010.

[13] **Jurčius A., Valiulis, A.V., Černašėjus O., Kurzydlowski K.J., Jaskiewicz A., Lech-Grega M.** Influence of vibratory stress relief on residual stresses in weldments and mechanical properties of structural steel joint. Journal of vibroengineering 12(1). Vilnius, 2010. P. 133-141.

[14] **Kocatepe K.** Effect of low frequency vibration on porosity of LM25 and LM6 alloys. Materials and design 28, 2007. P 1767-1775. (www.sciencedirect.com).

[15] **Liu Q., Zhai Q., Qi F., Zhang Y.** Effect of power ultrasonic treatment on microstructure and mechanical properties of T10 steel. Materials letters 61, 2007. P 2422-2425. (www.sciencedirect.com)

[16] **Chirita G., Stefanescu I., Soares D., Silva F.S.** Influence of vibration on the solidification behavior and tensile properties of an Al-18 wt% Si alloy**.** Materials and design 30, 2009. P 1575-1580. (www. elsevier.com/locate/matdes).

[17] **Limmaneevichitr C., Ponganpanya S., Kajornchaiyakul J.** Metallurgical structure of A356 aluminum alloy solidified under mechanical vibration: An investigation of alternative semi-solid casting routes. Materials and design 30, 2009. P 3925-3930. (www. elsevier.com/locate/matdes)

[18] **Luo W., Zhou N., Zhang Z., Wu H.** Effect of vibration force field on structure and properties of HDPE/CaCO3 nanocomposites. Polymer testing 25, 2006. P 124-129. (www.elsevier.com/locate/polytest).

[19] **Qu J., He G., He H., Yu G., Liu G.** Effect of the vibration shear flow field in capillary dynamic rheometer on the crystallization behavior of polypropylene. European polymer journal 40, 2004. P 1849-1855. (www. elsevier.com/locate/europolj).