STANDARD REMELTING METHODS OF THERMALLY SPRAYED NiCrBSi BASED COATING

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Abstract

Methodology of thermally sprayed coatings remelting is one of optional post-treatments which is capable of sealing surface porosity without using additives like polymers. One of its main advantages is ability to further improve the mechanical and corrosion properties of thermally sprayed coatings. The benefits derive from the positive influence on coating microstructure and removing inhomogeneities introduced into the coating during the thermal spraying process. The remelting methodology of coatings prepared by thermal spraying allows to reduce the inhomogeneities and the amount of porosity contained in the resulting coating, or to eliminate it entirely. The paper presents the results of mechanical properties evaluation made on samples of NiCrBSi alloy based coatings. Samples were deposited using thermal spraying technology (HVOF and FS) and remelted by standard methods (flame remelting, remelting by resistance, remelting in furnace). The resulting coatings were tested by ASTM G65 (abrasion wear resistance), ASTM G99 (Pin-on-disc), along with measurements of basic mechanical properties (HR15N, HV0.3, roughness). The microstructure of these samples was evaluated by optical microscopy.

Keywords: HP/HVOF, NiCrBSi, remelting, tribological properties, mechanical properties

1. INTRODUCTION

Thermally sprayed coatings are now widely used and available technology that provides the components with superior mechanical and anti corrosion properties. These technologies create functional coatings on components providing them with the desired enhanced properties. However, these enhanced properties can be further improved. The improvement is achieved by different methods of coatings remelting. The quality of the coatings deposited by thermal spraying methods depends on many parameters such as particle size, deposition temperature, fuel type, feed rate, spray angle, spray distance, substrate temperature, chamber pressure, spraying technique used and many others. In order to achieve the best results, all of these parameters have to be carefully adjusted. HVOF (High Velocity Oxy Fuel) and FS (Flame spray) are widespread and commonly used thermal spraying technologies. Both technologies produce coatings with a certain degree of porosity and both use similar powder materials. Coatings prepared using the FS technology are characterized by higher porosity and weaker adhesion to the substrate. These properties can be substantially enhanced by remelting methods. NiCrBSi coating was chosen for this study because it shows good results while subjected to heat treatment. This coating also exhibits excellent corrosion resistance due to the selective oxidation. The resulting oxides in pores block the pores and prevent the further penetration and diffusion of corrosive media to the substrate. Very low porosity of this coating and microstructure composed of flat splats also contributes to the increased resistance to high temperature corrosion at elevated temperatures (guaranteed especially by high content of Cr). These advantageous properties can be further improved by subsequent remelting of the coating, which is ensured by high content of B and Si (lower the melting temperature) [1, 2].

For this reason, NiCrBSi coating is widely used in applications requiring corrosion and oxidation resistance and mechanical durability. The resulting coating structure before the heat treatment is determined especially by the technology of coating preparation. The basic structure of commonly prepared NiCrBSi coatings contains pores, oxides and unmelted particles. Thanks to the unique composition of this coating, it is possible to eliminate these structural deficiencies by remelting techniques. The actual remelting of NiCrBSi coating further improves particular anticorrosion and antioxidation properties (due to the structure homogenization and the sealing of pores). The carbon contained in the coating allows the formation of carbides and improves the wear resistance [2]. Remelting by flame [3, 4], in furnace [5], by resistance and recently to the fore coming remelting by laser [5] are classic and most commonly used methods for remelting of coatings. The aim of this research is to evaluate the effect of different remelting methods on microstructure and mechanical properties of NiCrBSi coatings applied on steel substrate. The same NiCrBSi coating was applied on substrate using two different methods (HVOF and FS). The coatings were then remelted using three technologies. The impact of these technologies on the final properties of the coating was further evaluated in order to find the relationship between the remelting technology and the microstructure or mechanical properties.

2. EXPERIMENT

Experimental samples were prepared using two technologies (HVOF and 6PII). The prepared samples were then remelted using three standard methods which are remelting by flame, electrical resistance and in furnace. Samples were subsequently tested and evaluated in terms of mechanical properties and their microstructure was evaluated. Hardness (HR15N), micro hardness (HV0.3), roughness and tribological properties were included into mechanical properties testing. Preparation of samples, remelting and subsequent testing was performed in laboratories of Research and testing institute Plzen (VZU).

2.1. Deposition parameters

Standard optimized parameters were used for both HVOF and FS spraying technologies and NiCrBSi (M771.22) with a particle size distribution +20 - 53mm was selected as a powder material. The substrate surface was degreased and grit blasted before spraying (brown corundum F22 grit 0.8 to 1.0mm was used as an abrasive medium)

2.2. Measurement conditions

Microstructure evaluation was conducted by scanning electron microscope SEM (FEI Quanta 200) in NTC University of West Bohemia and by optical microscope Nikon Epiphot 300 in VZU Plzen. Surface hardness HR15N was evaluated by Rockwell HT 8003 hardness test on unpolished coating surface. Results were calculated as an average of five measurements conducted in laboratories of VZU Plzen. Micro hardness HV0.3 was evaluated in the coating cross section. Results were calculated as an average of seven measurements conducted similarly in VZU Plzen on LECO DM-400A device. Abrasive wear resistance measurements were conducted by Dry Sand Rubber Wheel test in VZU Plzen. The test parameters were following. Al2O3 sand (abrasive grain size 212-250 [μm]) was used as an abrasive material. Pressure force was 22N. Wheel speed was 180rev/min and the total measurement track was 718m. The test was conducted on the unpolished surface of samples. Wheel rubber was BR-60-z 10mm with hardness 60sh. Test procedure followed ASTM G-65 standard requirements [6]. Pin-On-Disc test was conducted in the laboratory of NTC ZČU according to ASTM G-99 standard. The test conditions were the same for all samples and the final value was calculated as an average of several measurements. Linear sliding speed was 10cm/s; load was 10N; balls had diameter of 6mm (steel and corundum balls were used); and samples were cleaned with ethanol. Slide track was constant during all tests (50 000 cycles). The environmental conditions with relative moisture and temperature were approximately Hr = 15 ± 20% a 20 °C, resp. and stayed constant during the test [7].

2.3. Remelting methods

Three remelting methods were selected to compare the influence of remelting on the resulting mechanical properties. The methods were remelting by flame, electrical resistance and in the furnace. Remelting by flame was carried out using an acetylene torch with a constant feed rate. The coating was heated up to optically evident melted state. Remelted coating was then cooled in air without additional cooling. This procedure was chosen due to the impossibility of precise coating temperature control during this method. Remelting in furnace was carried out under the predetermined conditions. Coated samples were heated to the temperature of 1025 °C commonly used for remelting of NiCrBSi coatings [4]. After reaching this temperature, 5 minute stay at the temperature 1025 °C followed, which should be long enough for coating remelting and homogenization. Subsequently, the samples were cooled by 5 °C per second until they were complete cooled.

Remelting using electrical resistance was carried out on the Smitweld device. This device uses standard samples of 10x10x100mm. However, it is not possible to perform abrasion resistance ASTM G65 tests on this sample size. For this reason, it was necessary to prepare a new geometry of samples (**Fig. 1**). This non-standard geometry proved to be very advantageous during the remelting. This geometry provides not only remelting in the central sample part, but the whole sample is heated uniformly to the desired temperature. In this way, the homogeneous remelting of the coating sample was achieved. The test conditions were foloing. The samples were heated up to a temperature of 1025 °C during one minute. During the test, it was possible to observe the progressive temperature gradient and its propagation direction from the ends of the sample to the middle. Samples were kept at the high temperature for 5 minutes and then cooled down by 5 °C per second. Remelting sequence is shown in **Fig. 1**.

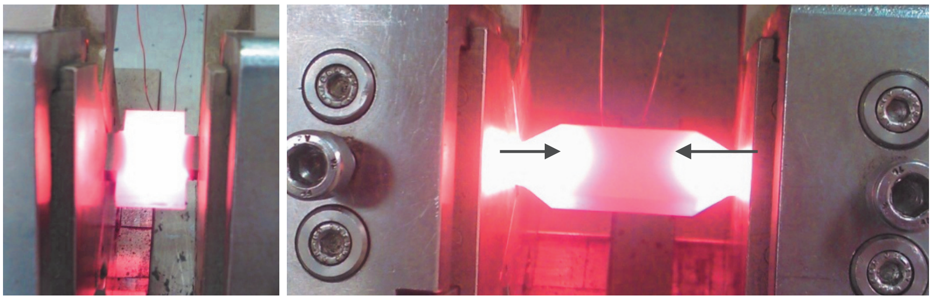

Fig. 1 Remelting using electrical resistance on samples with special geometry (process of sample heating is shown on the right figure)

3. RESULTS

3.1. Microstructure

The microstructure of samples is shown in **Fig. 2** (nominal magnification 500x). The figure shows that the coatings were remelted. The figure also shows complete change in coating microstructure. **Fig. 2a** shows the typical microstructure of FS coated sample before remelting. **Fig. 2b** shows the FS sprayed coating remelted by flame. This coating exhibits a clear reduction of porosity (the remaining pores are closed). The microstructure of this coating appears to be considerably finer and with obvious homogenization of structure, which is the crucial factor for final coating properties. **Fig. 2c** shows the FS sprayed coating remelted by electrical resistance. The microstructure does not show such changes comparing with **Fig. 2b**, but there can be still seen the refinement [8]. **Fig. 2d** (FS coating remelted using furnace) apparently shows significant coarsening of microstructure compared with previous technologies (**Figs. 2b and 2c**). There was also no greater reduction in porosity (pores does not exhibit any signs of sealing or spheroidization). It is assumed that the recrystallization occurs particularly in nickel stage [9]. **Figs. 2e and 2f** show HVOF sprayed coating remelted by electrical resistance method. The recrystallization is apparently not so strong compared with the coating deposited by FS, which is probably caused by the finer grain structure of the starting material. This way of coating remelting forms a transition layer composed of remelted Ni phases with the base material lying in the area between the coating and the base material [9].

Figs. 2g, 2h, 2i show HVOF coating remelted in the furnace together with the illustration of transient microstructure change from the surface of the coating to the substrate (from left to right). Outer layers (shown in **Fig. 2g**) content long recrystallized needles of Ni phase [9]. The last picture (**Fig. 2i**) shows the transition from coarse microstructure to a finer microstructure. The lower part of **Fig. 2i** indicates the interface melting between the coating and the substrate and the formation of a new transition region. This phenomenon is clearly noticeable on the black grains of corundum extending deep into this layer (corundum grains in the as-sprayed coating should be only on the substrate-coating interface).

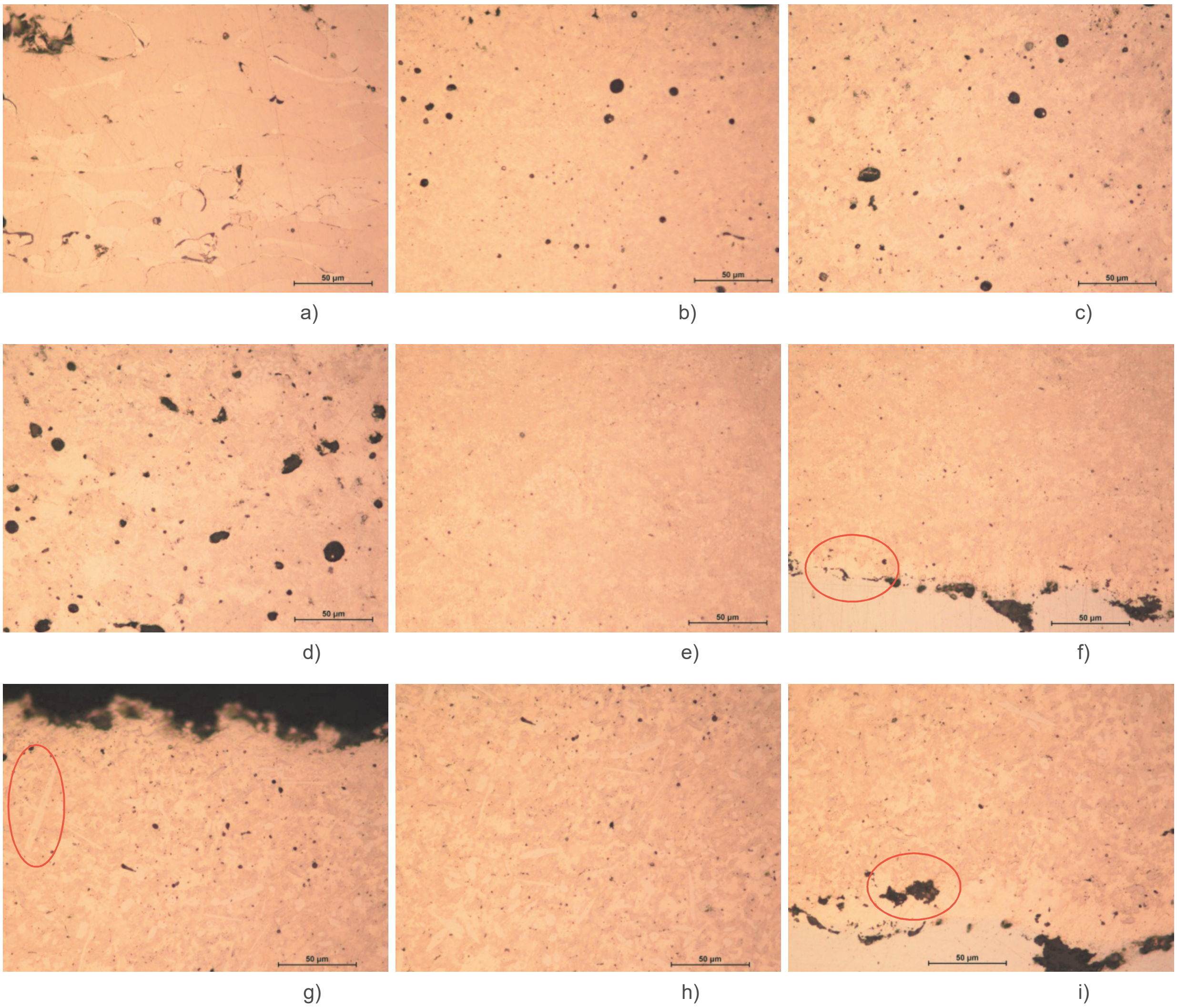

Fig. 2 Microstructure of coatings (a - FS coating without remelting; b - FS coating remelted using the flame; c - FS coating remelted by electrical resistance; d - FS coating remelted in the furnace; e, f - HVOF coating remelted by electrical resistance; g, h, i - HVOF coating melted in the furnace)

3.2. Mechanical properties

The measured values (see **Table 1**) indicate that the HVOF sprayed coatings have higher micro and macro hardness before and after the remelting compared with FS sprayed coatings. Measurements confirmed that macrohardness and microhardness are decreasing by coatings deposited using the HVOF technology during the remelting [7]. This phenomenon is attributed to the influence of relaxation of internal stresses which is being present in the coating prior to the remelting. The increase in hardness of coating prepared by FS technology is probably caused by the homogenization of the coating itself, because no remelted coating contained a plenty of pores which lowers the overall hardness. Furthermore, this variation is probably caused by measurement inaccuracy, because the hardness is very difficult to measure by the coating with large pores content. Significantly higher standard deviation points out this fact. In accordance with the assumption, the roughness of the coating was decreased after application of every remelting method. This phenomenon is caused by homogenization and increased coating compactness.

Table 1 Mechanical properties of remelted coatings

Technology	State	HR15N		HV0,3		Roughness [Ra]		Wear rate (Cumulative volume loss) [mm^3/m]
HVOF	As sprayed	87,78	± 1,83	815	± 58,76	6,72	± 0,95	0.0353 ± 0.00230
	Remelted by flame	86,48	± 2,12	859,86	± 70,67	1,32	± 0,33	0.0148 ± 0.00253
	Remelted by resistance	86,96	± 2,11	856,57	± 54,18	1,82	± 0,76	0.0153 ± 0.00320
	Remelted by furnace	82,98	± 2,41	789,29	± 60,68	2,52	± 0,45	0.0160 ± 0.00150
Flame sprayed	As sprayed	73,78	± 4,91	474,57	± 47,08	8,03	± 0,78	0.0319 ± 0.00143
	Remelted by flame	83,88	± 1,65	748,43	± 34,13	4,29	± 2,94	0.0242 ± 0.00241
	Remelted by resistance	82,46	± 1,02	760,71	± 41,71	2,61	± 0,34	0.0222 ± 0.00200
	Remelted by furnace	83,28	± 3,98	690,71	± 63,57	2,93	± 0,38	0.0195 ± 0.00130

3.3. ASTM G65 Abrasive wear resistance

Table 2 COF results of NiCrBSi remelted coatings

	Condition	Al2O3 ball		Steel ball	
FS	As-sprayed	0,702337	± 0,047551	0,72225	± 0,046403
	Flame	0,591616	± 0,027065	0,649149	± 0,050835
	Furnace	0,640897	± 0,053253	0,728347	± 0,061047
	El. resistance	0,6973	± 0,082804	0,77297	± 0,057391
HVOF	As-sprayed	0,664598	± 0,067611	0,697582	± 0,023820
	Flame	0,621814	± 0,042338	0,646084	± 0,024593
	Furnace	0,630177	± 0,076908	0,674322	± 0,072055
	El. resistance	0,603301	± 0,05192	0,555796	± 0,029138

Abrasion resistance of the coating is highly monitored parameter of coating mechanical properties. The measured results show a significant reduction in wear after the use of remelting methods. The rate of increase in abrasion resistance is depicted in **Table 1**. The decrease in wear rate was greater by the samples deposited by the HVOF compared with samples prepared by FS technology. Remelted HVOF samples show nearly the same results and do not exhibit significant variations in values. The samples prepared by the FS noticeably exhibit the deviations in values which depend on the use of specific remelting methods. This phenomenon is probably caused by high homogeneity and pores content in the microstructure of the FS coating. Not all methods were capable of pores elimination. While comparing macro and micro hardness with wear rate, it is obvious that the wear rate decreases with their increase. This fact demonstrates the best the coating sprayed by FS. Before the remelting, this coating has low hardness and high speed of cumulative wear. After remelting, this coating shows increase in hardness which is accompanied by decrease of wear rate.

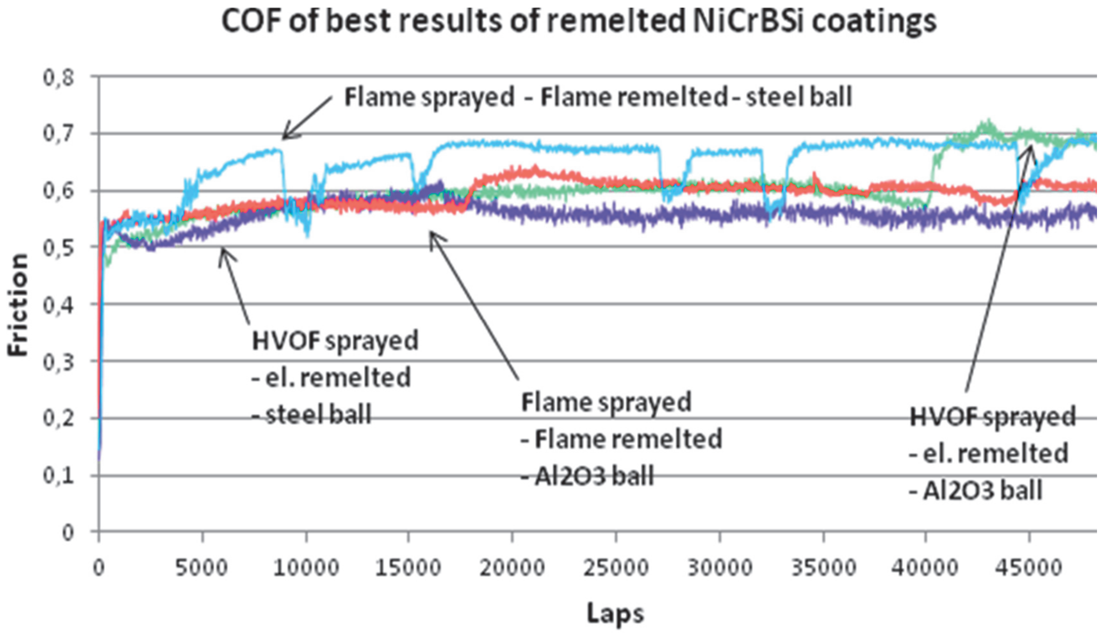

Fig. 3 Coefficient of friction of NiCrBSi remelted coatings with best results

3.4. ASTM G99 Pin-on-Disc test

Pin-on-Disc test was conducted on all as-sprayed and remelted coatings. The results of this test are shown in **Table 2**. Remelted coatings with best results deposited by both spraying technologies are compared in **Fig. 3**. FS coatings show a great reduction of friction coefficient after the remelting. Most significant reduction was obtained using remelting by flame. This decrease of friction is probably caused by achieving the most homogeneous microstructure and by elimination of pores. It is interesting that FS sprayed coatings after being remelted by flame exhibit the same level of friction as HVOF sprayed coatings. On other hand, coatings prepared by HVOF spraying technology did not show such significant reduction of friction coefficient. Only the HVOF coatings remelted using electrical resistance showed more significant reduction in friction coefficient. HVOF coatings are relatively dense and homogenous right after the deposition. It means that the homogenization processes do not significantly influence on resulting friction coefficient and its reduction has different reason. It is assumed that the slight reduction in friction coefficient is caused by the process of recrystallization ongoing in upper part of the coating during the remelting. This process is connected with the formation of new Ni phases [9]. This new microstructure has lower hardness but is dense and consists from long and coarse grains of Ni phases (**Fig. 2**). It is assumed that this is the main cause of the decrease in friction coefficient.

4. DISCUSSION

The complete remelting was achieved by using all methods. It was confirmed that the microstructure of coatings i influenced by the remelting method. Te best results (particle homogeneous structure) were obtained using the flame remelting. The resulting mechanical properties of coatings prepared by HVOF and FS technologies and subsequently remelted are quite identical. Only the coatings prepared using FS and remelted increased in their hardness. Abrasion resistance increases significantly regardless of the remelting method. Differences between remelting methods are especially evident in the resulting coating microstructure varying in the position and the size of particles and phases. When using the remelting in furnace, the formation of new transition layer on the coating-substrate interface occurs, and the upper layers exhibit strong recrystallization and growth of Ni phases. The most significant decrease in friction coefficient was observed by samples deposited using FS technology and remelted by the flame. It is assumed that this phenomenon is caused by coating homogenization and by elimination of residual pores. HVOF deposited and remelted coatings exhibit decrease in friction coefficient in the case of electrical resistance remelting. This should be result of recrystallization and formation of new Ni phases in upper parts of coating.

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