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Development of cold work tool steel based-MMC coating using HVOF spraying and its HIP densification behaviour

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ABSTRACT

The aim of the present study is to develop a Fe-based metal matrix composite (MMC) coating using high velocity oxy-fuel spraying (HVOF) process. A ledeburitic high alloyed cold work tool steel (X220CrVMo13-4) and NbC with an average size of 2 µm at different volume fractions have been considered as metal matrix and hard particles respectively. MMC coatings were deposited on austenitic stainless substrates and the coatings were subsequently densified by hot isostatic pressing (HIP) with and without encapsulation. Microstructural analysis of the as-sprayed and HIPed coatings were characterized by SEM and XRD methods. Results showed that the feedstock preparation involving fine NbC was an influencing factor on the coating deposition. A relatively homogeneous dispersion of fine NbC up to 30 vol.% in cold work tool steel matrix was possible using optimized HVOF spraying. Besides, HVOF spraying and its subsequent HIP treatment induced significant microstructural and phase changes in the MMC coatings. The study showed the potential of HVOF spraying for the development of steel based MMC coatings and its subsequent densification can be achieved by HIP process with and without encapsulation.

1. Introduction

Cold work tool steels have been used as hardfacing materials in roller presses for the mineral processing industry and extruders for transportation of polymer due to their high hardness and wear resistance. A further improvement of the wear resistance of cold work tools for high performance application can be realized when producing them as MMC with the incorporation of hard particles like NbC, TiC and Cr_3C_2. HIP cladding, generally referred as powder metallurgy (PM) coating, involves hot isostatic pressing (HIP) and has been considered as an important production route [1–3]. Type, size and volume fraction of hard particles can be optimized depending on the needs of application. In case of HIP cladding tools produced with cold work tool steel matrix, the volume fraction of hard particles up to 20 to 30% was found to be beneficial for noticeable improvement in the abrasive wear behaviour [2]. However, HIP cladding is a cost-intensive method as gas-tight HIP capsule has to be manufactured and furthermore, the dimensions of the coated component parts are depending on the maximum achievable furnace space [4]. The high hardness of gas atomized state cold work tool powders display low sintering capabilities and hence achievement of full density becomes difficult. Especially, HIP cladding is not a suitable method to apply coatings on complex geometries. In addition, development MMC involving ceramic hard particles is also difficult because achievement of full densification was realized while adopting supersolidus liquid phase sintering [5,6]. It is also observed that such a high temperature sintering leads to the possibility of dissolution of carbides in the matrix or reaction of carbides with the matrix carbides.

In this context, thermal spray processing could be an alternative to HIP cladding as it exhibits a flexible and cost effective possibility of coating on large components with complex contours [7]. Besides, widest range of materials like metal, alloys, ceramics, cermets and composites can be processed by means of thermal spraying. Among all thermal spraying methods, high velocity oxy-fuel spraying (HVOF) process has the tendency to form dense coating with closed porosity and with rather low oxidation. The subsequent HIP treatment following the HVOF spraying will lead to a more homogeneous microstructure in addition to a full densified coating. As coatings with closed porosity can be produced by HVOF, so an additional sealing or encapsulation of as-sprayed coatings might be avoided. This would also reduce the costs effectively. Few articles highlighted HIP densification behaviour of WC carbide based wear resistance HVOF coatings. Stewart et al. observed high rolling contact fatigue performance of HVOF sprayed WC-NiCrBSi coating after HIP densification [8]. They attributed the high performance to

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the microstructural improvement due to recrystallization, formation of complex carbides and improved bonding between the splats. Stoica et al. [9] performed sliding wear evaluation on HIP treated cermet coating sprayed by HVOF. Their HIP treated samples showed high wear resistance approximately twice that of the as-sprayed samples. This was attributed to the microstructural improvement due to phase transformation which leads to the elimination of complex secondary phases and the development of a metallurgical bonding between the constituent lamellae. Wielage et al. [10] pointed out that thermal spraying is a suitable technique for manufacturing of composite coatings with homogenous microstructure. Dewald et al. [11] review on thermal spray coatings indicated the recent success in modifying composite coatings by the formation of very fine dispersions of nano scale carbides to any desired fraction which can also be preserved in the microstructure of as-sprayed coatings.

Knotek et al. [12] studies on metal matrix composite developed by plasma spraying involving NbC hard particles emphasized the following requirements for ideal processing conditions: (i) wettability of hard particles with the matrix and (ii) no reaction between matrix and hard particles. In another study, Knotek [13] had pointed out that the main determining factor for improved wear resistance is not the hardness of matrix and carbides but matrix to carbide binding character. The use of NbC led to benefits as relatively high chemical and thermodynamical stability among other technically important hard particles [14].

The present study is aimed to develop a cold work tool steel based metal matrix composite (MMC) coating using HVOF. A ledeburitic type high alloyed cold work tool steel (X220CrVMo13-4) and NbC were used as metal matrix and hard particles, respectively. The effect of subsequent HIP densification with and without encapsulation was studied.

2. Experimental procedure

The present study used a high alloyed ledeburitic type cold work tool steel as a metal matrix with two different size fractions: 25 to 45 µm and 45 to 63 µm. The chemical composition of the powder is given in Table 1. MMC feedstock was prepared using cold work tool steel powder with the incorporation of fine NbC (2 µm) at varying volume fractions (10 and 30 vol.%) through a turbula mixing. The effect of mixing on the MMC feedstock was studied by using two mixing times (2 h and 24 h). HVOF coatings were performed using a DJ2600 (Sulzer Metco, Wohlen, Switzerland) gun on a 6-axis robot manipulator. The spray parameters are presented in Table 2. Austenitic stainless steel plates were used as substrate material and degreased before sand blasting and ultrasonically cleaned prior to coating deposition. To keep the substrate temperature low during spraying, air cooling was applied from the backside of the substrate. As-sprayed MMC coatings were subsequently densified by hot isostatic pressing. HIP treatment was carried out in argon atmosphere at a temperature of 1150 °C for 2 h with an isostatic pressure of 100 MPa. Microstructural examinations of sectioned as-sprayed and HIP treated coatings were performed using a scanning electron microscope (Ultra 55, Carl Zeiss NTS AG, Germany). Phase analysis of the powder and the coatings was carried out by X-ray diffraction (D4 Endeavor, Burke, Siemens, Germany) using CuK_α radiation.

Table 1
Chemical composition of cold work tool steel powder used for HVOF spraying.

Alloying element	C	Mn	Si	Cr	Mo	V	O	Fe
wt.%	2.25	0.30	0.60	13.50	1.00	4.00	0.014	Bal.

Table 2
HVOF spraying parameters used for the cold work tool steel coating.

Oxygen (SLPM)	Hydrogen (SLPM)	Carrier gas N_2 (SLPM)	Spray distance (mm)	Gun traverse speed (mm/s)	Particle size (µm)
150	630	14	200	500	25–45 and 45–63

3. Results and discussion

3.1. Influence of feedstock characteristics on the as-sprayed MMC coating microstructure

Properties of metal matrix and hard particles used in the present study are given in Table 3. Feedstock characteristics have a strong influence on the coating formation during thermal spraying. Especially, the resultant microstructure of the MMC coatings mainly depends on the physical properties such as density and particles size of the metal matrix and the hard particles that form the feedstock. When a large size and density mismatch exists between the metal matrix and the hard particles, there is a possibility that low density particles travel with a high velocity and may bounce off while hitting the substrate. This may result in a low bonding of hard particles in the metal matrix [8]. In the present study, a particle size mismatch exists while the density of tool steel matrix and NbC hard particles is rather equal. SEM images of two different feedstock prepared for MMC coatings are shown in Fig. 1. A reduction of the mean particle size in combination with agglomerations of fine NbC particles are evident as a consequence of the long duration of the turbula mixing as shown in Fig. 1a. On the other hand, a short duration leads to a relatively uniform distribution of metal matrix and hard particles with no significant reduction in size of the hard particle (see Fig. 1b). These feedstock characteristics are reflected in the microstructure of the MMC coatings as shown in Fig. 2. Fig. 2a & b show a cross-section of the MMC coatings produced from feedstock shown in Fig. 1a & b respectively. Their corresponding high magnification SEM images are presented in Fig. 2c & d.

To study the influence of the feedstock characteristics, the coating process was carried out using constant process parameters and a constant number of passes. Obviously, the thickness of the MMC coating produced with the agglomerated feedstock is significantly lower than that of the coating produced with non-agglomerated feedstock. A decrease in coating thickness while using agglomerated feedstock is attributed to the non-uniform powder feeding that was noticed during the spraying. Fine-agglomerated NbC particles show the tendency of grouping at the boundaries of melted and partially melted inter-splats while non-agglomerated particles are relatively homogenously dispersed.

3.2. HIP densification behaviour of HVOF sprayed MMC coating

Feedstock with a content of 30 vol.% NbC fine hard particles was considered for the investigation of the HIP behaviour. SEM micrographs of the as-sprayed and HIPed MMC coatings (with and without encapsulation) are shown in Fig. 3. The as-sprayed coating reveals a clean interface between substrate and MMC coating. The crack-free

Table 3
Properties of metal matrix and hard particles.

Properties	Metal matrix	Hard particles (NbC)
Processing route	Gas atomized	Sintered
Density (g/cc)	7.82	7.76
Melting point (°C)	1354	3608
Particle size (µm)	25–45 and 45–63	1–5