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Rolling contact fatigue of post-treated WC–NiCrBSi thermal spray coatings

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Abstract

The aim of this experimental study was to comprehend the relative rolling contact fatigue (RCF) performance and failure modes of functional graded WC–NiCrBSi thermal spray coatings in the as-sprayed and post processed state, by means of Hot Isostatic Pressing (HIPing) and vacuum heating. Functional graded WC–NiCrBSi coatings were deposited by a JP5000 system. HIPing was carried out at two different furnace temperatures of 850 and 1200 °C, while vacuum heating was performed at the elevated temperature of 1200 °C. The rate of heating and cooling was kept constant at 4 °C/min. Rolling contact fatigue tests were conducted using a modified four ball machine under various tribological conditions of contact stress and configuration, in full film elasto hydrodynamic lubrication. Results are discussed in terms of the relative RCF performance of the as-sprayed and post-treated coatings, and also surface and sub-surface examination of rolling elements using scanning electron microscope (SEM), light microscope and surface interferometry.

Test results reveal that performance of the coating was dependant on the microstructural changes due to post-treatment. Coatings heat-treated at 1200 °C displayed superior performance in RCF testing over the as-sprayed coatings at all stress levels (2, 2.3, 2.7 GPa) with emphasis on RCF performance at lower stress load of 2 GPa, where no failure occurred. Improvement in RCF performance was attributed to the diffusion between the carbides and matrix resulting in improved strength. At higher levels of contact stress, failure was surface initiated, and was attributed to initiation and propagation of micro-cracks at the edge of rolling contact region which led to coating delamination.

Keywords: Thermal spray; Hot isostatic pressing; Rolling contact fatigue; Failure modes

1. Introduction

There is an ever-increasing demand in the surface engineering industry to improve the operating performance of components, while maintaining or reducing the manufacturing costs. In many types of industrial appliances such as gears, camshafts and rolling element bearings, surface damage generated by rolling/sliding contact limits the life of the components and hence reduces durability and product reliability. This drives the development and implementation of state of the art surface coatings which can enable improved life reliability and load bearing capacity in more hostile environments.

Thermal spray coatings deposited by techniques such as the Detonation Gun (D-Gun), High Velocity Oxy Fuel (HVOF) and arc wire are used in many industrial applications requiring abrasion, sliding, fretting and erosion resistance. However, even using state of the art coating systems, it is not possible to achieve defect free thermal spray coatings. Difficulties arise due to the mismatch in elastic modulus, thermal expansion coefficients and hardness between the surface layer and the substrate material. This leads to the generation of residual stresses, which not only form during coating deposition but also arise during contact loading, and over time can cause coating delamination [1] and hence limit the use of thermal spray coatings to low stress applications. Voort [2] initially showed that thermal spray coatings not only have significant porosity but also secondary phase particles and a lack of fusion, which will not be eliminated using the FGM approach [3]. There are two kinds of pore geometry in thermal spray coatings, introduced by different mechanisms. One is lamellar poros-

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ity (elongated pores) at the lamellar or splat boundaries which is believed to arise from intermittent contact. The other types of pores are normally spherical in shape and arise from the expansion of trapped gases.

By applying a post-treatment, thermal spray coatings can be made more attractive to industry. Previous investigations have reported significant improvements in the coating microstructure at high Hot Isostatic Pressing (HIPing) temperatures [4]. The interlamellar porosity is completely eliminated while spherical pores, approximately 2 μm in diameter, are reduced to microvoids less than 0.1 μm in size. HIPing involves placing batches of coated samples inside a furnace which is contained within a pressure vessel. Temperatures of 1500 °C are possible while pressures of up to 200 MPa can be applied for a certain period of time. The coated samples are normally encapsulated in order to prevent surface cracking which can occur from the harsh conditions imposed by the HIPing process. However, this safety precaution technically restricts the shape and size of the samples which could be HIPed. Since emphasis in thermal spray technology is to continually search for cost effective solutions, an important objective in this analysis was to successfully HIP the coated samples without encapsulation. The principal aim of this investigation was to comprehend the relative rolling contact fatigue (RCF) performance and failure modes of functional graded WC–NiCrBSi thermal spray coatings in as-sprayed and post processed state.

Vacuum heating is another method of post-treatment which is similar to HIPing, but without the pressure, and can have a significant influence on the tribological performance of HVOF coatings [5]. At elevated temperatures, vacuum heating reduces porosity and oxide content within the microstructure, which results in increased coating densification and hardness [6]. Published research on vacuum heating is limited. Guo et al. [7] investigated the effect of vacuum heating on WC–NiCrBSi coatings. Results indicated that as well as a reduction in oxide content, porosity, micro-cracks and non-bond zones, porosity of the coating changed from continuous to discontinuous. The grains of the second phase became finer and more dispersive, and therefore, internal stress was decreased and improved by distribution. It was also indicated using Auger electron spectrometry that the NiCr binder diffused from the substrate to the coating. Hence in this investigation, in addition to the HIPing post-treatment, vacuum heating was also used to compare the relative performance and failure modes of as-sprayed and post-treated functional graded WC–NiCrBSi coatings.

Hence, by improving metallurgical bonding at splat and substrate interface levels, elimination of amorphous phases and micro-cracks as well as uniform compressive residual stress through out the coating microstructure [8], this can benefit both existing and novel industrial applications of thermal spray and HIPing in areas including rollers, shafts, drilling, mining equipment and especially harsh tribological environments such as the oil and chemical industry. To date, limited investigations exist on the influence of post-treatment on fatigue and delamination resistance in rolling/sliding contact [9]. In this study, functional graded WC–NiCrBSi coated discs were HIPed under the condition of the temperature range from 850 to 1200 °C and the pressure of 100 MPa. A number of coatings were also vacuum heated at 1200 °C, incorporating identical conditions of heating and cooling. A modified four-ball machine, which differs from the four-ball machine in the sense that the lower planetary balls are free to rotate was used to investigate the rolling contact fatigue performance under different tribological conditions. The failed rolling element coatings were analysed for surface failures using scanning electron microscope (SEM) and light microscope observations. The results are discussed with the help of micro-hardness measurements, indentation modulus analysis and surface interferometry.

2. Experimental procedure

2.1. Sample preparation

2.1.1. Powder processing and thermal spraying

Two types of agglomerated and sintered powders were prepared for the deposition of the functional graded coating. Specialised nickel alloy powder of composition Ni–7.56%Cr–3.69%Si–2.57%Fe–1.55%B–0.25%C and WC carbides less than 5 μm in size were manufactured to spray the graded coating. The powder-manufacturing route involved pre-alloying the powders which led to the formation of a spray-dried and sintered composite which was then sprayed onto the substrates. Pre-alloying has a number of inherent advantages over the other powder-manufacturing routes, e.g. mechanical blending. With mechanical blending, WC particles do not melt within the gun and hence on contact with the substrate rebound reducing the deposit efficiency. In sintered and agglomerated powders, deposit efficiency is thus significantly higher. Segregation during spraying leads to differences in specific gravity and particle size of each original powder with blending, hence, it is difficult to achieve a uniform structure in mechanically blended powders. The optimal route of pre alloying leads to a homogeneous structure. Coatings were deposited on 440-C bearing steel substrates with JP5000 HVOF system. Prior to the coating process , the substrate material was shot-blasted and preheated to increase the contact area for mechanical interlock and decrease the quenching stresses associated with the impacting lamella. Spraying was carried out using Kerosene as the fuel gas and oxygen as the powder carrier gas. The gun was kept fixed at a spray distance of 380 mm and the barrel length was measured at 4 in. The FGM consisted of two uniformed layers of approximately the same thickness. The FGM coating was graded