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Rolling Contact Fatigue of Hot Isostatic Pressed WC-NiCrBSi Thermal Spray Coatings

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Abstract

The aim of this experimental study was to comprehend the relative performance and failure modes of WC-NiCrBSi Thermal Spray coatings in As–Sprayed and HIPed (Hot Isostatically Pressed) conditions in rolling/sliding contact.

Recently a number of scientific studies have addressed the fatigue performance and durability of Thermal spray coatings in rolling/sliding contact, but as of yet there have been no investigations on Thermal Spray Coatings which have undergone the post treatment HIPing. The understanding of the mechanisms of failure in rolling /sliding contact after HIPing is therefore critical in optimising the parameters associated with this post treatment to achieve superior performance.

Coatings were deposited by a JP5000 system and HIPing was carried out at two different furnace temperatures of 1123K and 1473K. At both HIPing temperatures the rate of cooling was kept constant at 8˚C/minute. Rolling Contact Fatigue tests were conducted using a modified four ball machine under various tribological conditions of contact stress, configuration and lubrication. Results are discussed in terms of as-sprayed and HIPed surface examination of rolling elements using Scanning Electron Microscope (SEM) and Light Microscope.

Introduction

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

Thermal Spray coatings deposited by techniques such as detonation gun, High Velocity Oxy Fuel (HVOF), arc wire are used in many industrial applications requiring abrasion, sliding, fretting and erosion resistance. However, when a material is applied in the form of a protective coating, difficulties arise due to the mismatch in elastic module, thermal expansion coefficients and hardness between the surface layer and the base material. In high stress applications, such differences in material properties can lead to the generation of residual stresses, which have been shown in published literature to cause coating delamination [1].

Functional Graded Materials (FGM), when successfully applied, can influence the materials performance while maintaining or reducing fabrication costs. Several processing techniques have been explored for the fabrication of functionally graded materials such as powder metallurgy, adhesive bonding, in-situ synthesis, self propagating high temperature synthesis and thermal spraying [2-5]. Thermal Spray processing represents an industrially well established method and offers versatility and flexibility essential for the FGM design and process development. The main advantage of FGM's are that within the coating, peak stresses are lowered and stress singularities eliminated at certain crack sensitive locations. The composition of a functionally graded material is gradually distributed from the substrate to the surface which eliminates discontinuities of both temperature and stress profiles.

It is generally accepted that the microstructure of Thermal Spray coatings is highly dependant on the spraying method and parameters associated with spraying such as particle size, type of powder, velocity of spray etc. Voort [6] 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

[7]. There are two kinds of pore geometry in thermal spray coatings, introduced by different mechanisms. One is lamellar porosity (elongated pores) at the lamellar or splat boundaries which is believed to arise from intermittent contact. The other type of pores are normally spherical in shape and arise from the expansion of trapped gases. By applying a post treatment method to the coating termed Hot Isotatic Pressing (HIPing), densification can be significantly improved within the coating. 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 HIPing. However, this safety precaution restricts the shape and size of the samples. Since emphasis in Thermal Spray technology is to continually search for cost effective solutions, in this current study the coated samples were HIPed without encapsulation. In previous investigations on the effect of HIPing it has been seen that there is a significant improvement in the coating microstructure at high HIPing temperatures [8]. The interlamellar porosity is completely eliminated while spherical pores, approximatley 2 μm in diameter are reduced to microvoids less than 0.1 μm in size. This improvement in coating microstructure after HIPing is a result of the coating experiencing hot plastic deformation which causes the columnar grains to be broken into pieces forming many sub structures and crystal defects decreasing the system energy. After grain refinement either by static or dynamic recrystallization the newly formed equi axed grains are very small in shape due to incomplete grain growth . Combined with Hot Isostatic Pressure , these grains are compacted together hence, eliminating coating porosity.

It is important to investigate the durability of HIPed Thermal Spray coatings in rolling / sliding contact. Previous investigations of HIPed coatings indicate that significant improvement in the coating microstructure can be achieved by HIPing, yet to date no investigation to study the performance or failure modes of HIPed thermal spray coatings exist in published literature. This preliminary study hence, marks the first investigation in published literature in which the fatigue of HIPed functionally graded WC-NiCrBSi coatings are studied under different tribological conditions of contact configuration.

Prior to this study WC-NiCrBSi coated discs were HIPed under the condition of the temperature range from 1123K to 1473K and the pressure of 100 MPa. 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. The failed rolling element coatings are analysed for surface failures using Scanning Electron Microscope (SEM) and Light Microscope observations. The results are discussed with the help of microhardness measurements and elastic modulus analysis.

Coated Disc Test Elements

A liquid fuel HVOF (JP5000) system was used to deposit the functionally graded WC-NiCrBSi coatings on the surface of 440-C discs. The coating and substrate materials were selected because of their desired synergy of mechanical and thermal properties. The substrate discs were 31 mm in diameter and 8 mm thick. The substrate material was sand blasted prior to the coating process to improve the adhesive strength due to the increased bonding contact area and the mechanical interlock between the substrate material and the overlay coating. After spraying coating thickness was 400 μm. However, after grinding and polishing coating thickness was reduced to give an average coating thickness of 300 μm. The discs were then Hot Isostatically Pressed (HIPed) at two different temperatures of 1123K and 1473K in unencapsulated conditions. The heating and cooling rate for both cycles was kept constant at 8˚C/minute in order to prevent surface cracking. A constant pressure of 100 MPa on the samples was maintained for 1 hour by Argon gas being pressurised against the surface of the discs. Under these conditions none of the coatings exhibited any signs of surface cracking.

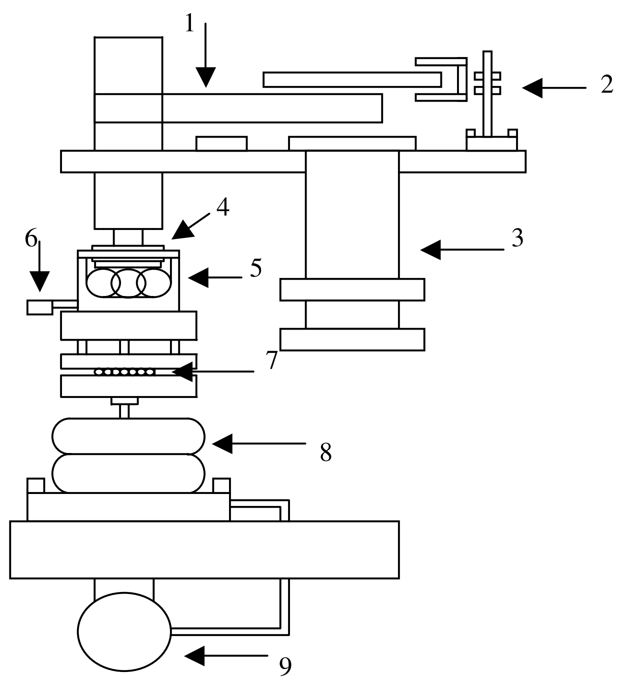


Figure 1: Schematic of the modified four-ball machine.
(1, Belt drive; 2, speed sensor; 3, Spindle driving motor; 4, coated disc and collet; 5, cup assembly; 6, Thermocouple; 7, thrust bearing; 8, bellows; 9, Pressure Gauge)

Rolling Contact Fatigue (RCF) Tests

A modified four ball machine, as shown in Figure 1 was used to investigate the RCF performance of HIPed functionally graded thermal Spray coatings. This modification enabled the rotation of the planetary balls to correctly model the kinematics of rolling element discs and precisely defined the contact load. In the current setup, the coated rolling element disc replaced the upper drive ball, which represented the inner race of the rolling element ball bearing. The coated discs were ground and polished to attain a root mean square (RMS) surface roughness of 0.1± 0.05 µm. Planetary balls were commercial grade 12.7 mm diameter 440-C bearing steel or hot Isostatically pressed silicon nitride ceramic, with a surface roughness of 0.01± 0.005 µm. These two materials were used to conduct RCF tests in conventional steel ball bearing (steel planetary balls) and hybrid ceramic bearing (ceramic planetary balls) configurations. RCF tests were conducted under full film lubrication conditions, at a spindle speed of 4000 ± 10 rpm, and at an ambient temperature of approximately 25˚C. Failure was defined as the increase in vibration amplitude above a pre set level. A high viscosity lubricant, Vitrea 320, was used in all of the tests. .

Experimental Results

RCF Test Results

RCF tests were conducted in a variety of triboligical conditions of contact stress, and contact configuration on As-Sprayed, HIPed at 1123K and HIPed at 1473K coated discs. Table 1 summarises typical tribological conditions and RCF results. Results summarised in Table 1 are selected from a battery of tests to comprehend the performance and ascertain the failure modes under various tribological conditions and are not intended for statistical fatigue life prediction.

Surface Observations of Failed Rolling Discs

Figure 2 shows the surface of a failed As-Sprayed WC-NiCrBSi disc subjected to a stress of 2 GPa (Test T1). Figure 2(a) shows the area of failure under light microscope while Figure 2(b) is from SEM and displays the area of failure in more detail.

Figure 3. shows the surface observation of an As-Sprayed disc subjected to a higher contact stress of 2.7 GPa (Test T2). Figure 3(a) shows an overall view of the area of failure. Using SEM, Figure 3(b) gives a more detailed image of the failure.

Figure 4 shows the surface observation of an As-Sprayed disc also subjected to a stress of 2.7 GPa (Test T3). However, the planetary balls are now ceramic. Figure 4(a) shows the surface observation. Under closer inspection a number of cracks can be detected near the pit and are located in the centre of the wear track (Figure 4(b)).

Figure 5. shows the surface observation of a failed coated disc which was HIPed at 1123K and subjected to a contact stress of 2.7 GPa using steel planetary balls (Test T5). Figure 5(a) shows the area of failure which has spread outwith the confines of the wear track. The steep walls of the pit, which can be observed at higher magnification, indicate significant depth (Figure 5(b)).

Figure 6, shows the surface observation of a failed disc also HIPed at 1123K and subjected to a contact stress of 2.7 GPa (Test T6). The planetary balls were ceramic. Figure 6(b) shows the formation of a significant pit which has spread out with the wear track. Figure 6(b) shows evidence of macro cracks forming within the centre of the wear track near the area of failure.

Test No	Contact Load (F) (N)	Planetary Balls	Contact Stress (Po) (GPa)	Test Lubricant	Duration of Test (minutes)	No of Stress cycles (millions)	Failure Type
AS SPRAYED TESTS							
T1	130	Steel	2	Vitrea 320	555	6.1	Spalling
T2	310	Steel	2.7	Vitrea 320	60	0.7	Spalling
T3	310	Ceramic	2.7	Vitrea 320	20	0.2	Spalling
HIPed at 1123K TESTS							
T4	130	Steel	2	Vitrea 320	500	5.5	Delamination
T5	310	Steel	2.7	Vitrea 320	157	1.7	Delamination
T6	310	Ceramic	2.7	Vitrea 320	72	0.8	Delamination
HIPed at 1473K TESTS							
T7	130	Steel	2	Vitrea 320	6360	70	None ▲
T8	310	Steel	2.7	Vitrea 320	229	2.5	Spalling
T9	310	Ceramic	2.7	Vitrea 320	555	6.1	Spalling

Table 1: Rolling Contact fatigue tests for as sprayed, HIPing at 850°C and HIPing at 1200°C HVOF coated rolling elements on bearing (440-C) substrate.
▲ suspended test after 70 million stress cycle

Figure 7 shows the surface observation of a unfailed coated disc HIPed at 1473K and subjected to a stress of 2 GPa using steel planetary balls (Test T7). Figure 7(a) shows the wear track at low magnification. Figure 7(b) shows the wear track failure at higher magnification

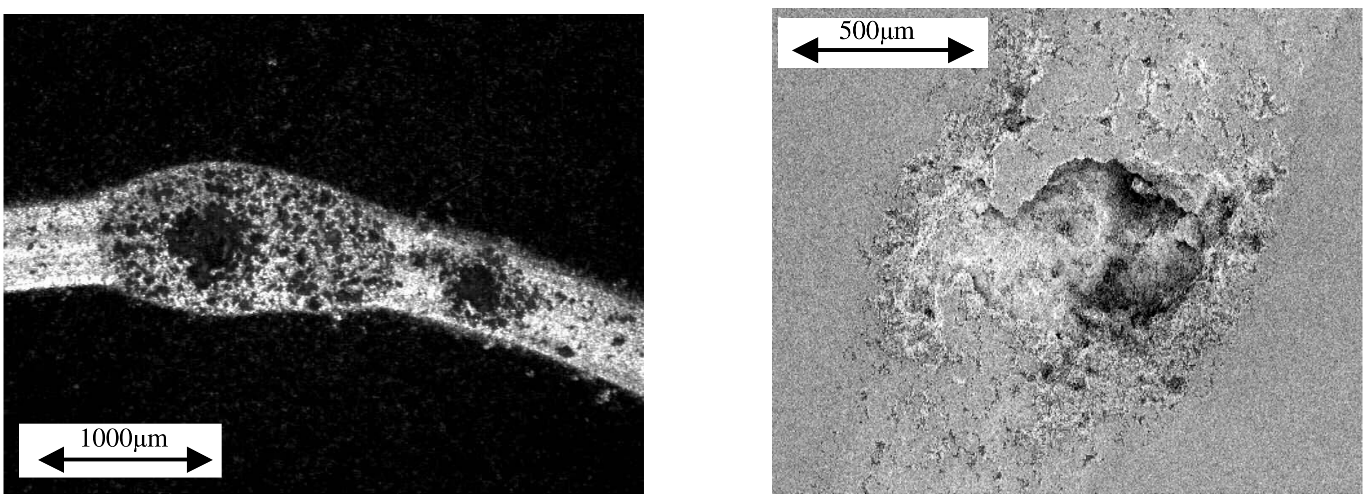
Figure 8 shows the surface observation of a failed coated disc HIPed at 1473K and subjected to a stress of 2.7 GPa using steel planetary balls (Test T8). Figure 8(a) shows that the area of failure was within the wear track. Figure 8(b) shows the area of failure at higher magnification.

Figure 9. shows the surface observation of a failed disc HIPed at 1473K and subjected to a stress of 2.7 GPa using ceramic planetary balls (Test T9). Figure 9(a) displays the overall view of failure. Figure 9(b) shows a number a macro cracks near the area of failure and at the centre of the wear track.

Microhardness Measurements

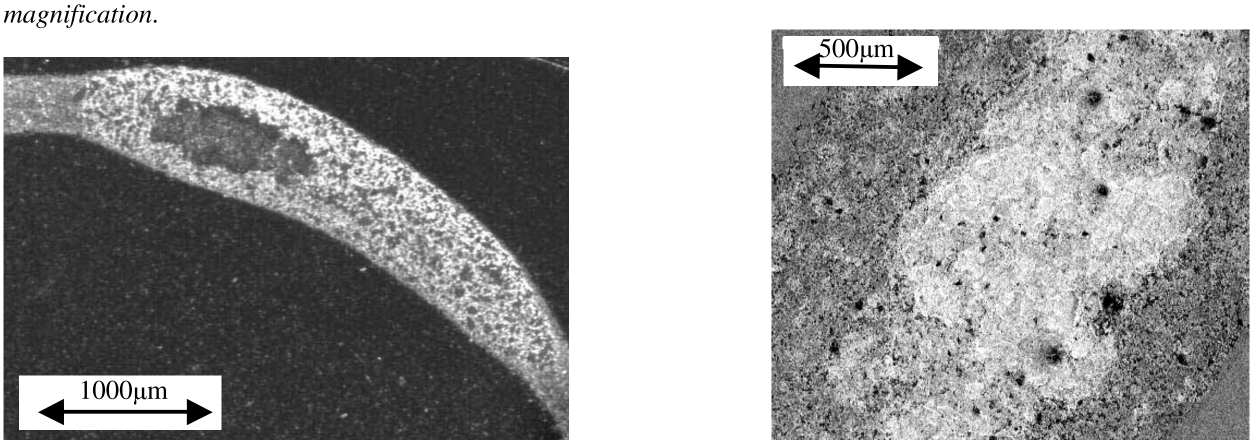
Microhardness and Elastic Modulus measurements were taken on the surface and cross section of As-Sprayed, HIPed at 1123K and HIPed at 1473K coated discs. Hardness measurements were taken on the coating surface at a test load of 500 mN and on the cross section of the coatings at 500 mN. Results are displayed in Figure 10. Results from the As-Sprayed coating show a surface hardness of 780 N/mm². In comparison results from the surface of the coating HIPed at 1123K display an increased hardness of 1040 N/mm². Increasing the HIPing temperature to 1473K lead to an increased surface coating hardness of 1110 N/mm².

Elastic Modulus results are shown in Figure 11. Results from the surface of the As-Sprayed coating displayed an average value of 250 GPa. Results from the surface of the coating HIPed at 1123K displayed a slightly higher value of 300 GPa. On increasing the HIPing temperature to 1473K , a slight increase in the elastic modulus was observed from surface measurements. Cross sectional analysis of the coatings displayed an increase in elastic modulus away from the



(a) (b)

*Figure 2: Surface Observation of As-Sprayed WC-NiCrBSi disc (Test T1); **(a)** overall view of failed area; **(b)** area of failure at higher magnification.*



(a) (b)

*Figure 3: Surface Observation of As-Sprayed WC-NiCrBSi disc (Test T2); **(a)** overall view of failed area; **(b)** area of failure at higher magnification.*

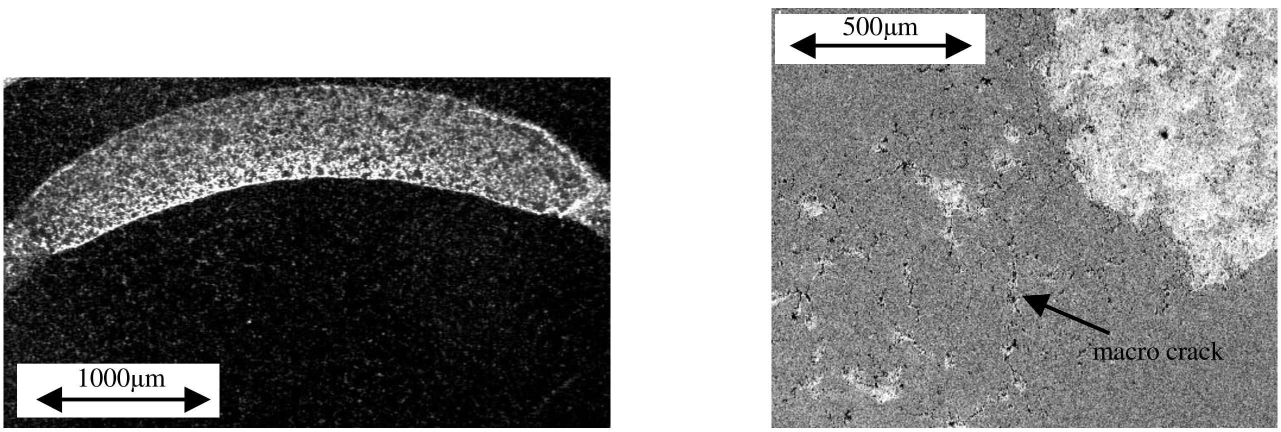
coating surface in the HIPed coatings. This trend was observed in the As-Sprayed coating. It is highly likely that this increse was related to the effect of HIPing since a more significant increase in Elastic Modulus was observed at higher HIPing temperatures.

Discussion

Classification of failure modes was made on the basis of Surface Observations of the failed coated discs using SEM and Light Microscopy. Post test examination is the only method to ascertain failure modes and mechanisms. The principal aim of this current study was to ascertain whether similar failure modes occurred in post treated coatings as had been previously seen in As-Sprayed Thermal Spray coatings. Classification of Thermal Spray coatings has been categorised into four main modes and named as abrasion, Delamination, bulk failure, and Spalling. However from post test analysis only two modes of failure were identified. They were delamination and spalling.

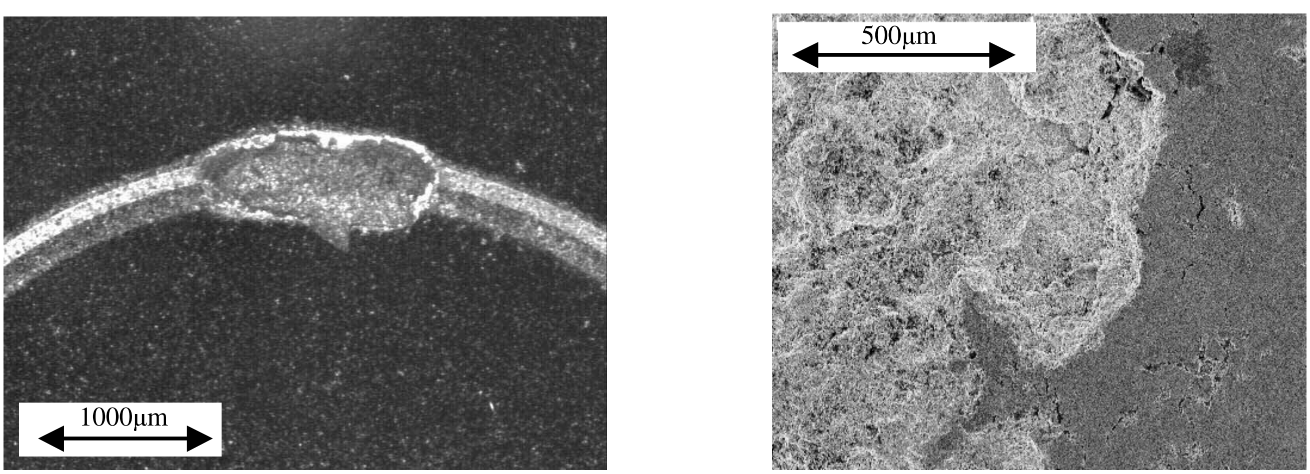
Suh initially proposed a delamination theory of sliding wear in 1973. Suh [9], Flemming and Suh [10] have since performed experimental and theoretical analysis supporting the delamination theory. The mechanism of delamination wear includes the propagation of cracks parallel to the surface at a depth governed by material properties and friction coefficient. Although rolling friction prevails in modified four ball tests and delamination theory is based on sliding friction, the results are still compelling. Damage theory of materials begins with the premise that a material contains a multitude of defects in the form of microvoids [11] which undergo extension due to loading and unloading. A similar approach is adapted to explain the mechanism of coating delamination.

Spalling is the most commonly seen failure in conventional steel element bearings. Spalling fatigue however, is the rarest mode of fatigue failure in Thermal Spray coatings. Tallian [12] defined a spall as a sharp edged steep walled flat bottomed feature formed by the fracture of a surface. A spall



(a) (b)

*Figure 4: Surface Observation of As-Sprayed WC-NiCrBSi disc (Test T3); **(a)** overall view of failed area; **(b)** edge of failure and macro cracking in wear track.*



(a) (b)

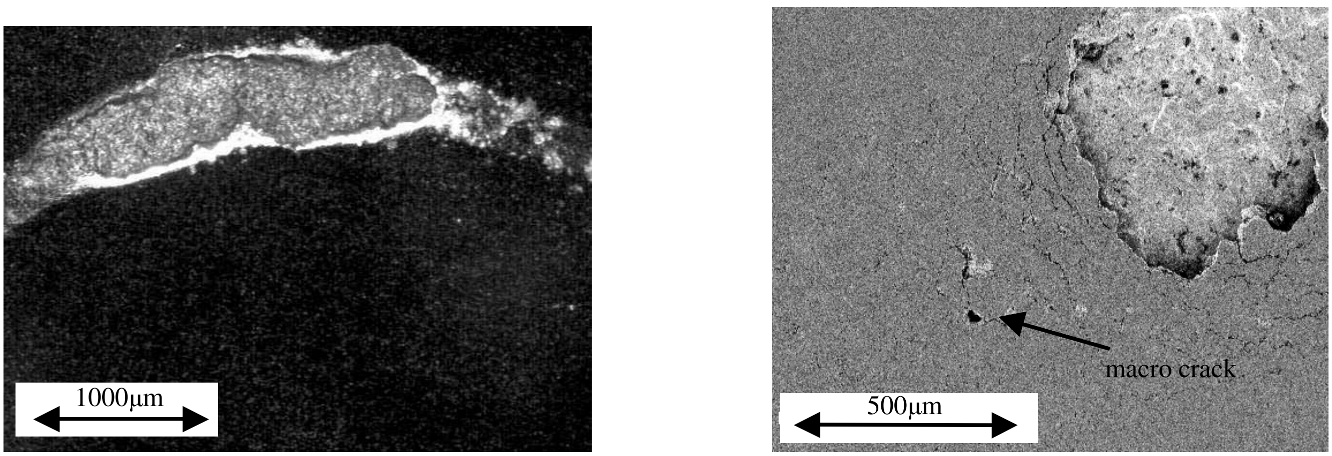
*Figure 5: Surface Observation of HIPed at 1123K WC-NiCrBSi disc (Test T5); **(a)** overall view of failed area; **(b)** edge of pit at higher magnification..*

in Thermal Spray coatings resembles in appearance to the spalls in conventional bearings and it differs from delamination failure. The spall is contained within the wear track and is circular or elliptical in appearance, with its surface area (width to depth ratio) much smaller than that of a delaminated coating. Spalls can initiate from micropits, furrows, grinding marks or dents on the surface of a wear track. In addition subsurface inclusions and defects are known to lead to spalling of rolling elements.

Influence of HIPing

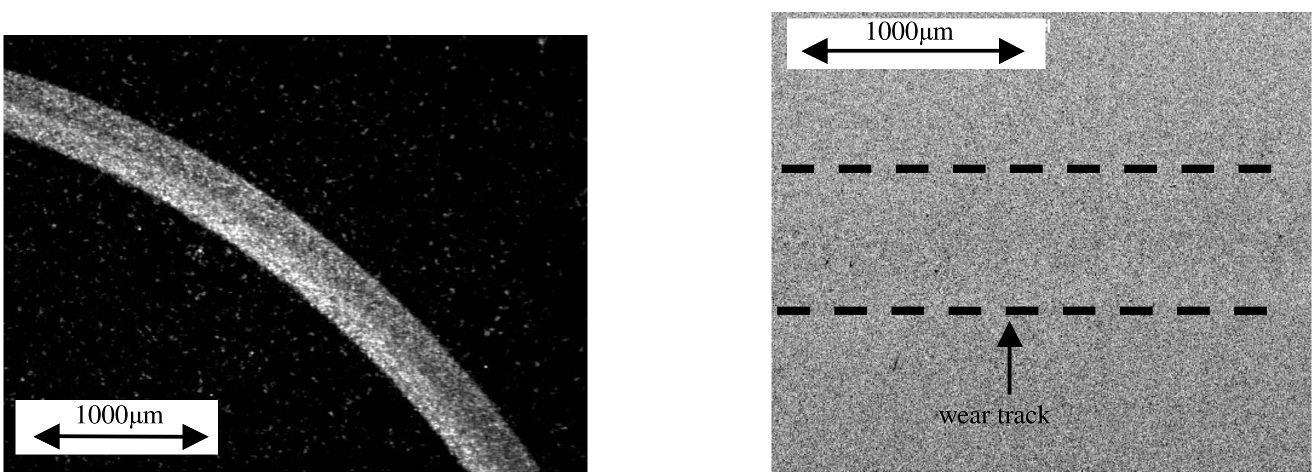
RCF tests were performed on As-Sprayed WC-NiCrBSi coatings at two different levels of contact stress. Figure 2 shows the surface observation of the failed disc subjected to a stress of 2 GPa. From initial analysis it appears that delamination is the main mode of failure since the area of failure is greater than the width of the wear track. However, with closer inspection it can be seen that failure has resulted from a spall within the wear track. The debris from this initial spall has formed a high frequency of macropits which surround the spall and also a number of larger pits within the wear track. At a higher contact stress the mode of failure has not changed (Figure 3). The effect of increasing the contact stress has lead to the formation of a more significant spall which in turn has lead to more macro pits forming from the subsequent increase in volume of debris from the initial spall.

Figure 6 shows the surface observation for a failed disc HIPed at 1123K and subjected to a stress of 2.7 GPa. The effect of HIPing has changed the mode of failure. A significant pit has formed and spread out with the wear track. The walls of the pit are relatively steep indicating significant depth. From these characteristics, the mode of failure is concluded to be delamination. It is highly likely that failure was initiated by subsurface defects but this theory will require confirmation from sub surface analysis.



(a) (b)

*Figure 6: Surface Observation of HIPed at 1123K WC-NiCrBSi disc (Test T6); **(a)** overall view of failed area; **(b)** edge of pit at higher magnification.*



(a) (b)

*Figure 7: Surface Observation of HIPed at 1473K WC-NiCrBSi disc (Test T7); **(a)** overall view of wear track; **(b)** wear track at higher magnification..*

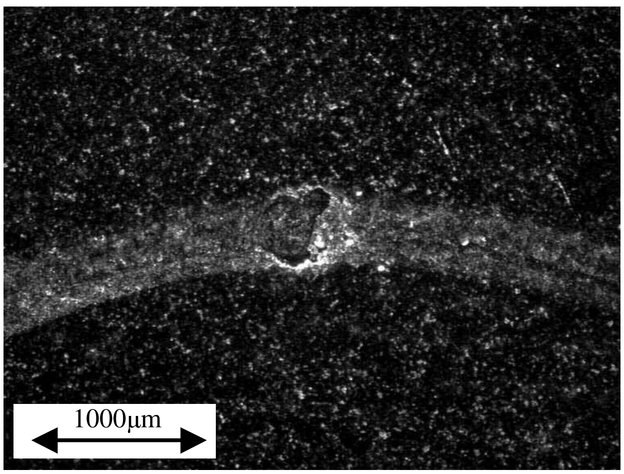
Figure 7 shows the wear track of a disc HIPed at 1473K and subjected to a stress of 2 GPa.using steel planetary balls. NO failure was detected by either light microscopy or SEM analysis. This is an important result since it shows that when functionally graded WC-NiCrBSi coatings are exposed to high temperatures during HIPing significant improvement in resistance to rolling contact fatigue occurs.

Figure 8 shows the surface observation for a failed disc HIPed at 1473K and subjected to a stress of 2.7 GPa. It can be seen that the mode of failure has changed in increasing the HIPing temperature. The pit which has formed is smaller in size and is restricted to within the wear track. Under higher magnification the sides of the pit appear relatively steep and the bottom of the pit is flat. These characteristics suggest that in fact the pit is a spall. It is highly likely that failure initiated from a surface defect since Microhardness and Elastic Modulus results aswell as previous investigations on the coating microstructure [8] rule out the possibility of sub surface defects.

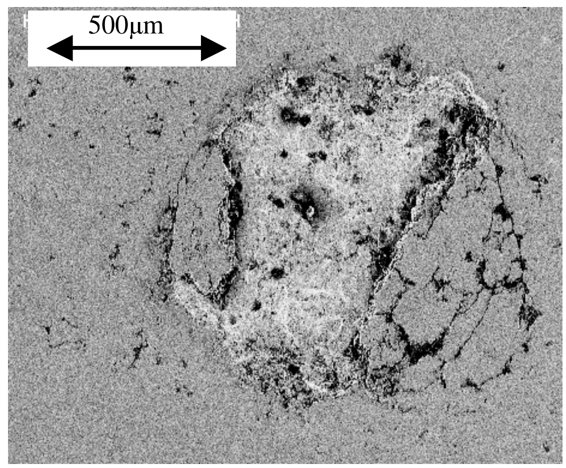
Influence of Contact Pair Hardness

When RCF tests were conducted in a hybrid ceramic bearing configuration, the higher hardness of the ceramic balls resulted in severe micro cracking of the coating material.

Figure 3 shows the surface observation of a failed WC-NiCrBSi disc subjected to a stress of 2.7 GPa using ceramic planetary balls. A number of macro cracks are visible using SEM near the area of failure. Under Light Microscope the area of failure appears to be delamination but with closer inspection the area of failure has formed from a high frequency of macro pits. It is highly likely that the formation of the macropits were initiated from the macro cracks within the wear track.

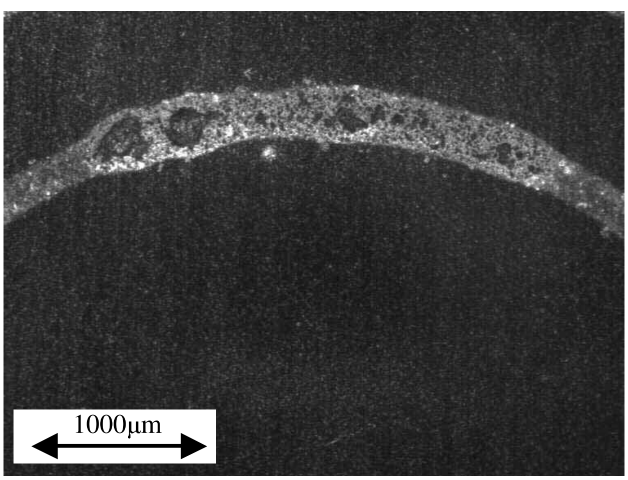


(a)

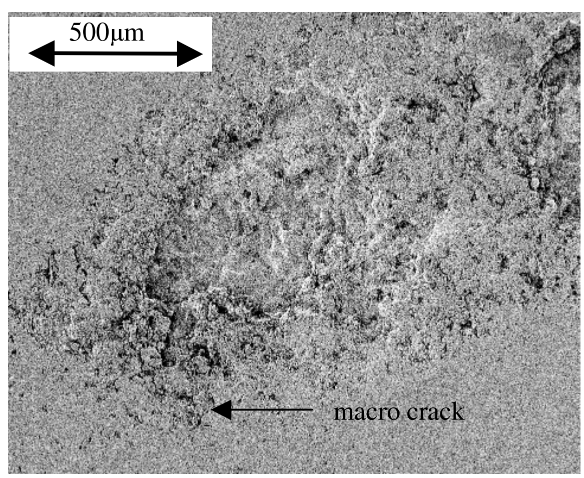


(b)

*Figure 8: Surface Observation of HIPed at 1473K WC-NiCrBSi disc (Test T8); **(a)** overall view of failed area; **(b)** area of failure at higher magnification..*



(a)



(b)

*Figure 9: Surface Observation of HIPed at 1473K WC-NiCrBSi disc (Test T9); **(a)** overall view of failed area; **(b)** area of failure at higher magnification..*

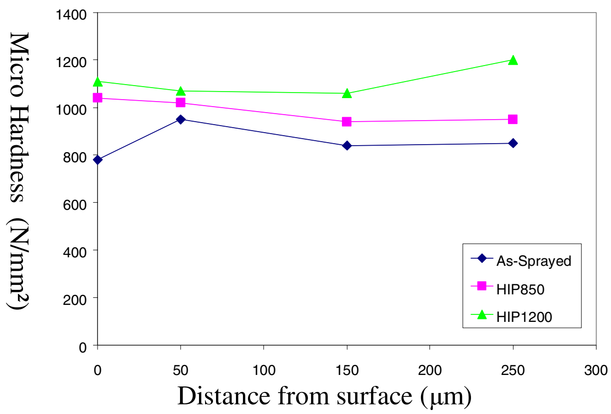


Figure 10: Hardness Results for As Sprayed, HIPed at 1123K and HIPed at 1473K Coatings.

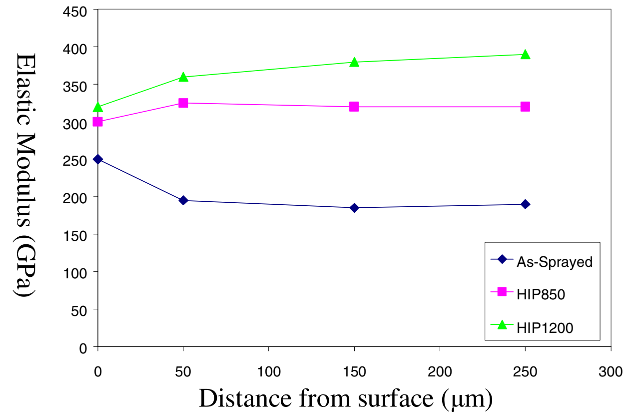


Figure 11: Elastic Modulus Results for As Sprayed,HIPed at 1123K and HIped at 1473K Coatings.

Figure 6 shows the surface observation of a failed disc HIPed at 1123K tested under identical conditions. It can be seen that the mechanism of failure has changed. A pit has formed with steep sides and significant surface area. The mode of failure was concluded to be delamination. A number of macro cracks were also visible near the area of failure.

Figure 9. shows the surface observation of a failed disc HIPed at 1473K and subjected to a stress of 2.7 GPa using ceramic planetary balls. It can be seen from both the SEM and Light Microscope images that the mode of failure is no longer delamination. Failure has resulted from the formation of a spall within the wear track . The debris from the initial spall has formed subsequent macro pits and dents within the wear track. The SEM image shows a number of macro cracks near the spall. It is highly likely that these cracks initiated the formation of the initial spall.

Conclusion

Two modes of fatigue failure were identified as Delamination and Spalling.

Analysis of the failed As-Sprayed coatings indicated spalling as the main mode of failure. Failure is likely to have been initiated from sub surface defects in the tests conducted using steel planetary balls due to the inherent porosity of the coating microstructure which has been verified by previous investigations aswell as Microhardness and Elastic Modulus results. In the test conducted using ceramic planetary balls the mode of failure remained constant but it is more likely that macro cracks within the wear track initiated failure rather than sub surface defects as the time to failure was so rapid.

Delamination was identified as the main mode of failure in the coatings HIPed at 1123K. The theory of delamination indicates that failure was initiated by surface defects however sub surface analysis is required in order to confirm this theory.

WC-NiCrBSi coatings HIPed at 1473K did not fail when subjected to a stress of 2 GPa. This is an extremely encouraging result as it shows that functionally graded WC-NiCrBSi coatings can be incorporated in high stress industrial applications if the coatings are post treated at high temperatures of HIPing At higher levels of contact stress and with variation of planetary ball type, the mode of failure was identified as spalling. However, due to the significant improvement in coating microstructure it is highly likely that failure was initiated by surface defects although sub surface analysis is required to fully verify this conclusion.

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