Wear-mapping to optimize overlay coating design in rolling sliding contacts

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ABSTRACT

The design of surface coatings for tribological applications in rolling sliding contacts not only requires a thorough understanding of the tribological conditions e.g. contact stress, lubrication and friction but also the influence of coating processes, material, thickness and the role of substrate material properties. Tribologists often have little choice about the former but can significantly influence the coating performance by appropriate selection of the latter. This research paper addresses the benchmark design requirements of such overlay coatings produced by thermal spraying process and introduces the wear map based upon the understanding of failure modes. Results presented here give a generic understanding of the performance and design parameters of cermet coating design for rolling sliding contacts, and thus represent a step forward in the development of future overlay coatings for high stress applications.

List of symbols

b = Minor axis of the contact ellipse (μm)
ξ = Average coating thickness (μm)
Ψ = Depth of maximum shear stress (μm)
P_o = Peak compressive stress (Pa)
H_{av} = Average coating substrate hardness (Pa)
σ = Substrate yield stress (Pa)
λ = Non-dimensional film thickness (H_{min} / R_{qa})
Δ = Non-dimensional coating thickness (ξ/ψ)
δ = Non-dimensional pressure (P_o/σ)

R_{qa} = Average RMS roughness of contacting bodies (μm)

Abbreviations

APS	Air Plasma Spraying
D-Gun	Detonation Gun
HVOF	High Velocity Oxy-Fuel
RCF	Rolling Contact Fatigue
RMS	Root Mean Square

1 INTRODUCTION

Overlay coatings hold a niche in surface engineering technology and its UK market is estimated to be in excess of £20 billion within the next four years. Within this family of overlay coatings, thermal spray coatings have provided cost effective and environmental friendly solutions to a variety of surface engineering problems, including restoration of undersized/worn components, and replacement of environmentally hazardous chrome plated coating process for the landing gears in aerospace industry. Ever increasing tribological applications of thermal spray coatings such as friction dampers, steel mill rolls, engine cylinders, and drilling tools benefit from the high abrasive, erosive, and corrosive wear resistance of these coatings. The diversity of thermal spraying processes coupled with the extensive range of available coating materials e.g. from carbide based abrasive wear resistance coatings to polymer based abradables, have enabled them to hold a niche in surface engineering technology. However, conventional materials and manufacturing processes used for tribological applications involving Hertzian stress distribution, such as rolling bearings, dies, gears, rollers, shafts, drilling/mining equipment, especially those working in hostile tribological environments e.g. oil, chemical and food processing industry are at the limit of established technology. There is a growing demand to utilise the innovative advancements in the field of surface engineering e.g. vapour deposition and thermal spray coating technology, to provide efficient, reliable, and environmental friendly solutions in these applications. To accomplish this, a combination of material/tribological properties is required, not achieved by other processes. Functionally graded coatings produced by the vapour deposition process represent an excellent solution for production tooling and small sized components. Thermal spray coatings however have the capability to deposit much thicker coatings and on large sized components, at a fraction of cost of the former. This has made thermal spray coatings competitive in the production market. Albeit these advantages, research to explore their true potentials for high stress tribological applications is in its infancy.

Generic understanding of performance indicators and failure modes can thus provide a step forward to develop future coatings and extend the spectrum of applications to high stress components. Hence, instead of providing Rolling Contact Fatigue (RCF) test results for evaluating and predicting the statistical fatigue life, the aim of this investigation was to provide generic information on the performance and failure modes of thermal spray WC-Co coatings in rolling sliding contacts. This information was then used to benchmark design requirements of overlay coatings by introducing a wear map based upon the understanding of failure modes.

2 EXPERIMENTAL TEST PROCEDURE

2.1 Thermally sprayed rolling elements

Thermally sprayed WC-12%Co coatings deposited by three commercially available processes i.e. Detonation Gun (D-Gun, SDG2040), High Velocity Oxy-Fuel (HVOF, JP5000) and High Velocity Plasma Spraying (HVPS, GG-WC-102) were considered in this investigation. These coating processes were selected because of their differences in impacting lamella speed and temperature, and thus provided a broad range of average particle speed and temperature for this investigation. To minimise the effect of coating process conditions on the fatigue failure modes, industrially optimised practices of process parameters for each of the coating process was used in this investigation. The coating material was selected on the basis of its high hardness and proven resistance to sliding wear. These coatings were deposited in a thickness range of 20 to 250µm. Coating thickness was varied to investigate the influence of location of shear stresses above or below the interface during the contact loading. The substrate material was either 440-C, M-50 bearing steel or mild steel in the shape of rolling element ball or cone. This enabled the investigation of substrate hardness variations on the failure modes of thermally sprayed rolling elements. Substrates bearing steel balls were commercial grade 12.7 mm diameter whereas, the rolling element cones were machined to 14.5 mm in diameter with an apex angle of 90° and 109°. These variations in the substrate shape and cone angle affected the roll/slip ratio. 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 within the impacting lamella. Except in the case of M-50 steel substrate, where the pre-heat temperature was lowered to 50°C to avoid softening of substrate material, coatings were produced at a substrate pre-heat temperature of around 150°C.

2.2 Rolling contact fatigue (RCF) tests

A modified four-ball machine, shown as Figure 1, was used to investigate the RCF performance and failure modes of thermally sprayed rolling elements. This modification allowed the rotation of the planetary-balls to correctly model the kinematics of rolling element ball bearings and precisely defined the contact load. In the current set-up, the coated rolling element cone or ball replaced the upper drive-ball, which represented the inner race of rolling element ball bearing. These coated rolling elements were ground and polished to attain a Root Mean Square (RMS) surface roughness of 0.1±0.05 µm (R_q). Planetary balls were commercial grade 12.7 mm diameter 440-C bearing steel or hot isostatically pressed silicon nitride ceramic, having surface roughness of 0.01±0.005 µm (R_q). 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 immersed lubrication conditions, at a spindle speed of 4000±10 rpm and at an ambient temperature of 24°C. Failure was defined as the increase in vibration amplitude above a pre-set level. Two test lubricants i.e. Hitec-174 and Exxon-2389 were mainly used in the testing program. Hitec-174 is a high viscosity hydrocarbon oil having a kinematic viscosity of 200 mm^{2}s^{-1} at 40°C and provided a full film lubrication regime under the test conditions adapted for this study. Exxon-2389 is a commercially available synthetic oil having a kinematic viscosity of 12.4 mm^{2}s^{-1} at 40°C and lubrication regime with this lubricant was mixed.

2.3 Post RCF-test investigations

Post RCF investigation investigations included Scanning Electron Microscope (SEM), die-penetrant, interferometry and residual stress investigations. These investigations were carried out to provide a thorough understanding of failure in WC-Co coatings as discussed in the next section.

3 RESULTS and DISCUSSION

3.1 RCF failure modes

Previous investigations relating to the RCF failure modes of thermal spray coatings included work by Nieminen et al. [1] and Nakajima et al. [2]. These investigations have classified the fatigue failure modes on the basis of surface and sub-surface observations in the pre and post RCF conditions. Ongoing tribological investigations of failure modes in thermal spray coatings by the authors [3-6], using the modified four ball machine, indicated four distinct failure modes i.e. abrasion, delamination, bulk failure and spalling (Figure 2). These coatings can fail in either one or a combination of these modes depending upon the tribological conditions of contact stress, configuration and lubrication. The following subsections provide a summary of these failure modes, details of which can be seen in afore mentioned references [3-6].

3.1.1 Abrasive failure of coated rolling elements

The combined effect of micropitting and surface wear on the wear track of components in rolling sliding contacts is collectively termed as abrasive failure in thermal spray coatings. A typical example of this failure is shown in Figure 2a. Non-contacting three-dimensional interferometry of failed wear track indicated that the micropits leading to abrasive failure were on average 50 μm wide and a maximum of 5 μm deep. Abrasive failure mode in thermal spray coatings is thus not significantly different to those associated with Rolling Contact Wear (RCW) in conventional steel bearings, e.g. Balu [7] has considered RCW as nucleation sites for initiating RCF. Littman et al. [8] has characterised similar failure as 'peeling' during a study of fatigue failure modes of conventional steel ball bearings whereas, Tallian [9] has characterised this type of failure as surface distress. In spite of the various terminologies used to distinguish similar failure in steel bearings, the underpinning failure mechanism is associated with asperity contact in the presence of microslip within the contact region. Gross sliding, though not necessary for this type of failure, is thought to promote micropitting.

3.1.2 Delamination failure in thermal spray coatings

Suh initially proposed a delamination theory of sliding wear in 1973 [10]. Fleming and Suh [11], Suh and Saka [12] and Suh [13] 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 RCF tests and delamination theory of wear is based on sliding friction, nevertheless the similarities of the failure mechanism in both cases are compelling. Typical observation of coating delamination at the coating substrate interface can be seen from Figure 2b. Sheet-like debris which reached a few millimeters in major dimensions are produced during this process. The mechanism of coating delamination during RCF failure involves crack initiation at the location of maximum and orthogonal shear stress in the subsurface region. Once initiated, these cracks propagate circumferentially at their respective depths until they reach a critical length before surfacing to cause delamination failure. For relatively thinner coatings, where coating thickness is of the order of the depth of maximum shear stress, failure is generally abrupt and catastrophic at the coating substrate interface, also termed as adhesive delamination. Contrary to this behaviour, relatively thicker coatings generally show cohesive delamination, i.e. delamination within the coating material.

3.1.3 Coating failure due to bulk deformation

Bulk deformation of substrate material is of primary importance for the cases of hard coatings on a soft substrate. This is because the contact stress can be in the elastic range of the coating material and plastic range of the substrate. The primary effect of this is the plastic flow of substrate, leading to conformity of contact region and, a hump at the edge of wear track. Figure 2c shows a typical example of such failure, in which the substrate could no longer support the coating, leading to bending and cracking of coating material in the initial stages of RCF failure. As cyclic loading continues, the coating cracks in the middle of wear track due do its inability to plastically deform under tensile stress caused by the plastic flow of substrate material. During this failure, the plastic flow of substrate continues and the substrate is pushed up at the edges of wear track, as it conforms to the geometry of counter body, leading to subsequent cracking at the edge of wear track. Further cyclic loading leads to crack propagation in tension and substrate finally emerges at the edge of wear track. As the crack propagation is progressive due to cyclic loading, this failure mode is categorised as a RCF failure mode. Once the conformity of contact is such that the stresses in the substrate are no longer in the plastic region, the substrate migration terminates and a steady state is reached. The mechanism of bulk deformation is thus strongly depended upon the ability of substrate material to support the coating in relation to the contact stress and is marginally affected by the changes either in coating material or process.

3.1.4 Coating failure due to spalling

Spalling is the most commonly seen RCF failure in steel rolling element bearings. Spalling fatigue is however the most rare mode of fatigue failure in thermal spray coatings. Spall in thermal spray coatings resemble in appearance to the spalls in conventional bearings as shown in Figure 2d, and it differs from delamination failure (discussed above) in the sense that spall is contained within the wear track and, it is circular or elliptical in appearance with its surface area (or width to depth ratio) much smaller than that of delaminated coating. A comparison of Figures 2b and 2d can distinguish the appearance between the two failures. As with conventional steel bearings, spalls in thermal spray coatings can initiate from micropits, furrows, grinding marks or dents on the surface of a wear track. Also, subsurface inclusions and defects are known to lead to spalling of rolling elements. Examination of the wear track of spalled specimen in thermal spray coatings indicate that substantial micropitting of the wear track occurs before fatigue spall is produced. This highlights the possibility that the fatigue spall in thermal spray coatings initiates from the micropits and subsequent crack propagation takes place due to cyclic loading. It is also possible that once initiated, crack propagation can be assisted by the Hydraulic Pressure Propagation (HPP) [14] to assist spalling. However, the exact mechanism of fatigue spall i.e. surface or subsurface initiation and propagation in thermal spray coatings is not completely understood at this stage.

3.2 Design considerations

The design of surface overlay coatings for tribological applications involving Hertzian loading not only requires a thorough understanding of the tribological conditions e.g. contact stress, lubrication and friction but also the influence of coating processes, material, thickness, and the role of substrate material properties. Tribologists often have little choice about the former but can influence the coating performance by appropriate selection of the latter. This section thus provides some insight into the design considerations of coating/substrate material properties, coating thickness, and coating processes to combat RCF failure and thus enable the generation of wear map (next section).

3.2.1 Substrate material

The mechanism of bulk deformation and interfacial delamination failure mode indicated that the four most important design considerations whilst selecting the substrate material were:

- ability to support the coating.

- a higher coefficient of thermal expansion than the coating material to induce a certain degree of compressive residual stress within the coating material.
- ability to withstand pre-heat temperature prior to thermal spraying.
- ability to plastically deform during shot penning, prior to thermal spraying, to promote mechanical interlock at the coating substrate interface.

The ratio ($\delta = P_o/\sigma$) of the Hertzian contact stress (P_o) to the substrate yield strength (σ) was thus found critical in determining the ability of the substrate to support the coating. Figure 3 shows this effect and indicates that normalised[1] contact stress (P_o/σ) can be used to benchmark candidate substrate materials.

As the substrate steels considered in this study had almost twice the coefficient of thermal expansion than that of the coating material (WC-Co), there was no significant difference in the residual stress fields generated by these substrates. However, residual stress fields were significantly altered by the process conditions such as cooling between passes and preheat temperature for a given coating substrate system. Such process conditions can thus be integrated into the coating design process. Experimental measurements of residual stress field in these coatings indicated that an average compressive residual stress of approximately 1500 MPa could be achieved within the coating material by appropriate selection of process parameters [4]. Coatings sprayed to provide a similar degree of compressive residual stress performed better than those without it. This is consistent with other studies e.g. in hybrid ceramic bearings a compressive residual stress combats tensile cracking during fatigue failure. However, too high a compressive residual stress can be detrimental as coatings can have a premature failure.

3.2.2 Coating thickness

Investigations of delamination failure mode (both cohesive and adhesive) indicated that whilst selecting the coating thickness for a given coating substrate system, it was critical to shift the maximum and orthogonal shear stresses away from the coating substrate interface. Using this technique also simplified the design by not having to functionally grade the material to avoid the sharp stress gradient at the interface during the Hertzian loading. Hence the ratio ($\Delta = \xi/\Psi$) of the average coating thickness (ξ) to the depth of maximum shear stress ($\Psi = 0.65$ b) was found to be a good indicator of the coating substrate system to combat interfacial delamination. Figure 4 shows this effect, and indicates that Δ value can have a significant influence on the fatigue performance of HVOF coatings.

3.2.3 Coating material

Investigation of failure modes indicated that the selection of a hard wear resistant coating material requires a consideration of its coefficient of thermal expansion, and the ability of the coating process to produce a dense coating microstructure for the selected coating material. Within the boundaries of WC-Co materials considered in this research, and its comparison with previously investigated ceramic (Al_2O_3) coatings [15], results indicated that the cermet coatings

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[1] A trend similar to Fig. 3 was observed if the contact pressure is normalised by the average coating substrate hardness (H_{av}).

performance was superior to that of the ceramic coatings. This was mainly because of the following three reasons:

- lower melting point of cermet material allowed melting of lamellas during the HVOF processes, whereas ceramic was partially melted, resulting in a lower cohesive and adhesive strength.
- higher temperatures during the APS process although melted the ceramic particles, velocities achieved are generally much lower than the HVOF system, resulting in porous microstructure and thus lower strength.
- higher lamella temperature during the APS process would have a high rate of cooling (quenching) upon impact with underlying surface, which can lead to internal cracking.

These factors contributed towards lower adhesive and cohesive strength of ceramic coating and indicated the need for an interfacial layer. With the advancements of high velocity plasma systems, it may however be possible to use ceramic materials in the future.

3.2.4 Coating process (es)

The most important consideration whilst selecting the coating process for high stress applications was its ability to produce a dense coating microstructure, resulting in higher mechanical strength. Although there are a number of ways to analyse this, e.g. porosity measurements, x-ray diffraction pattern, microhardness and bond strength etc., this research has indicated that a useful measure for high stress applications was to compare the indentation fracture toughness (K_{IC}) of the coating material, produced by various spraying processes. So far, WC-Co coatings with an indentation fracture toughness $K_{IC} \geq 1.7$ $MNm^{-3/2}$ have shown a fatigue life in excess of 70 million stress cycles for a coating design parameters of $\Delta \geq 1.5$ and $\delta \leq 1.5$.

4 WEAR MAPPING

Based upon the understanding of failure modes and design considerations of Hertzian contact stress (P_o), coating thickness (ξ), depth of maximum shear stress (Ψ) and the substrate yield strength (σ), it was possible to create the wear map as shown in Figure 5. This wear map have the non-dimensional axes of normalised pressure ($\delta = P_o/\sigma$) and coating thickness ($\Delta = \xi/\Psi$). Although other axes are also possible to plot this map, the selected parameters were found to have the most significant influence on the coating performance and failure modes. The influence of lubrication film in the mixed and full film regime is represented as the second x-axis. The boundaries indicated by these failure modes are not rigid and the undefined areas on the map indicate that the failure mode will be a combination of these failures, depending upon the boundaries in the vicinity of undefined area. The area enclosed within the rectangle marked on the wear map indicates the design criteria to be avoided, as the failure can be abrupt and catastrophic in that region. The wear map also indicates safe design conditions, where it has been possible to achieve a performance beyond 70 million stress cycles without failure. The reliability of thermal spray coatings can however be compromised by the presence of tiny flaws, such as microcracks within the coating microstructure. Although, recent innovations in thermal spray technology have indicated that it is possible to achieve almost negligible porosity within the coating microstructure, thermal spray coatings in general exhibit relatively poor bonding at the interface of unmelted/partially-melted splats. This can compromise the fracture toughness of the coating. Process modifications such as High Density Infrared (HDI), and hybrid laser systems are yet to show realistic advantages in terms of improved fatigue resistance. Post-treatment of these coatings can thus provide the much needed macroscopic homogeneity in the coating microstructure. This can not only result in properties similar to that of the bulk material, but also push the boundaries of safe operating region to higher contact stress levels.

5 CONCLUSIONS

- Wear map of thermal spray coatings in rolling sliding contacts has been introduced which indicates that the influence of coating design and tribological conditions on the failure modes is significant.
- By appropriate selection of coating substrate system, coating thickness, and process, it is possible to achieve a fatigue life in excess of 70 million stress cycles.
- Investigation of failure modes has indicated that thermal spray coatings can fail in one or a combination of the four failure modes namely abrasion, delamination, bulk failure and spalling.

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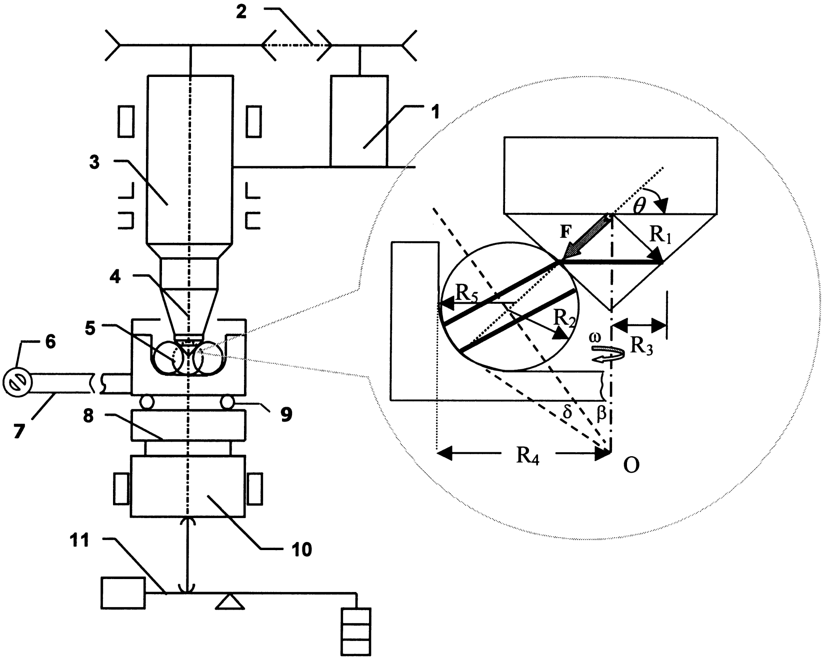

Figure 1, Schematic of modified four-ball machine showing ball cone cup assembly,
(R_1=R_2=6.35mm, R_3=3.65mm, R_4=14.2mm, R_5=7.62mm, θ=35.15°, δ=25.33°, β=29.52°)
(1, driving motor; 2, belt drive; 3, spindle; 4, coated cone and collet; 5, cup assembly; 6, force transducer; 7, torque arm; 8, heater; 9, thrust bearing; 10, loading piston; 11, loading lever)

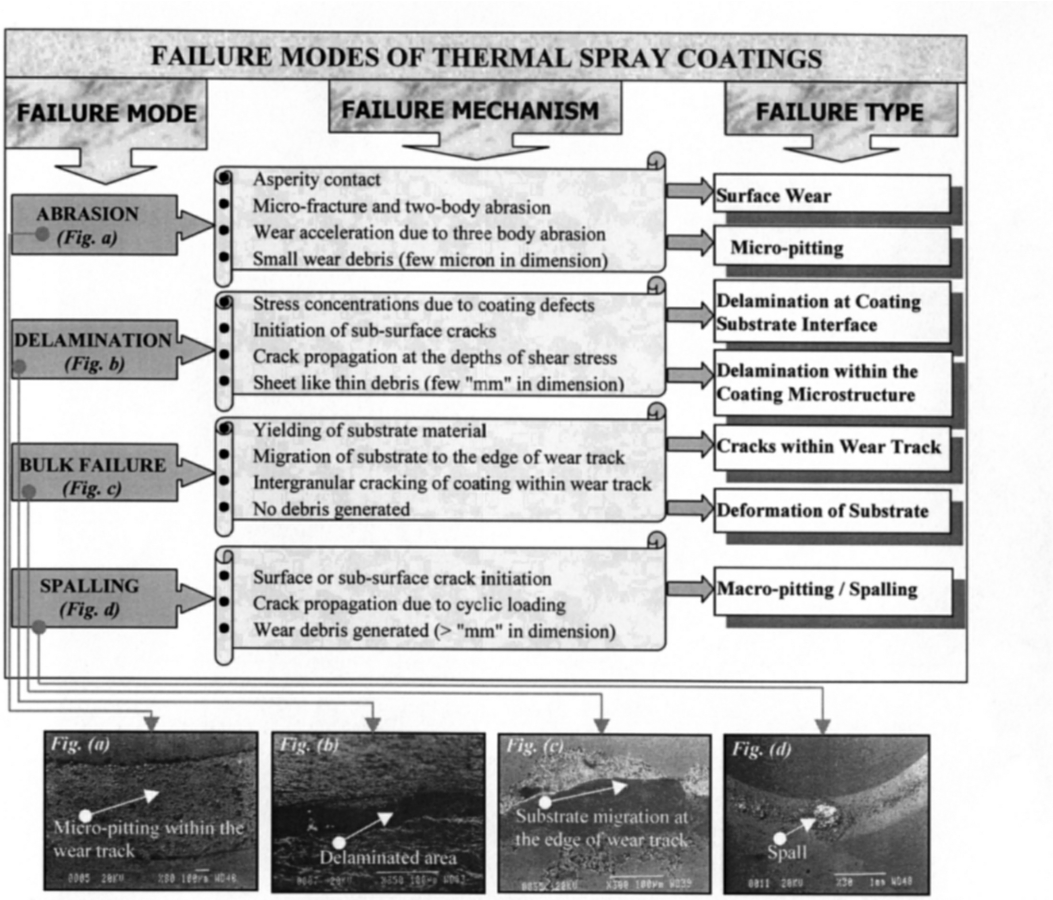

Figure 2, Fatigue failure modes of thermal spray coatings in rolling sliding contacts.

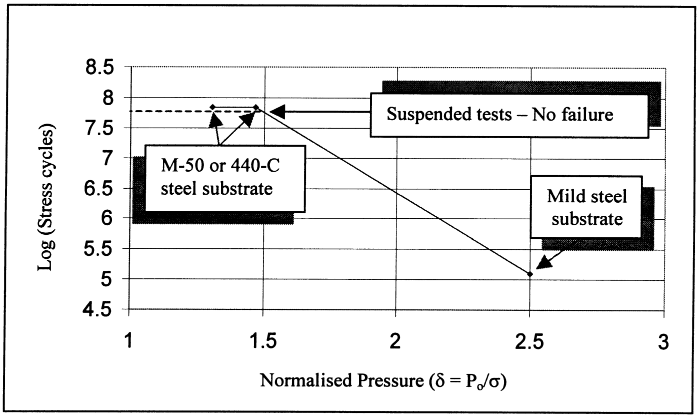

Figure 3, Influence of normalised pressure on stress cycles ($\Delta \geq 1.5$, $P_o = 2.7$ GPa)

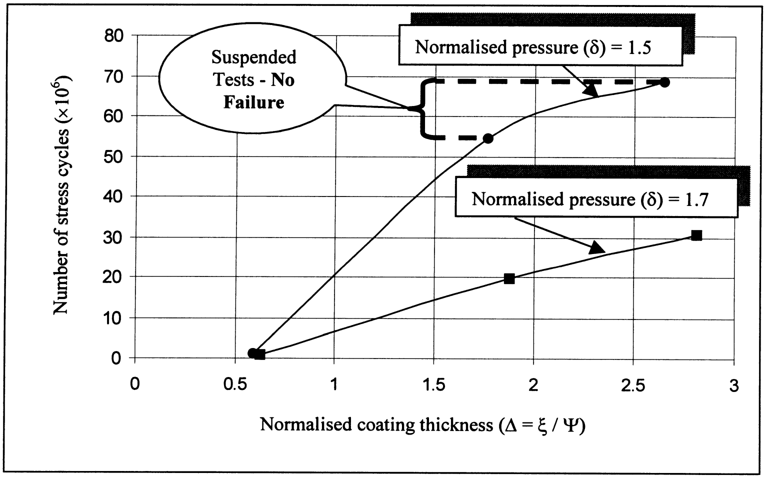

Figure 4, Influence of normalised coating thickness on coating performance, (Coating produced by HVOF process on 440-C steel substrate ($\sigma = 1840$ MPa))

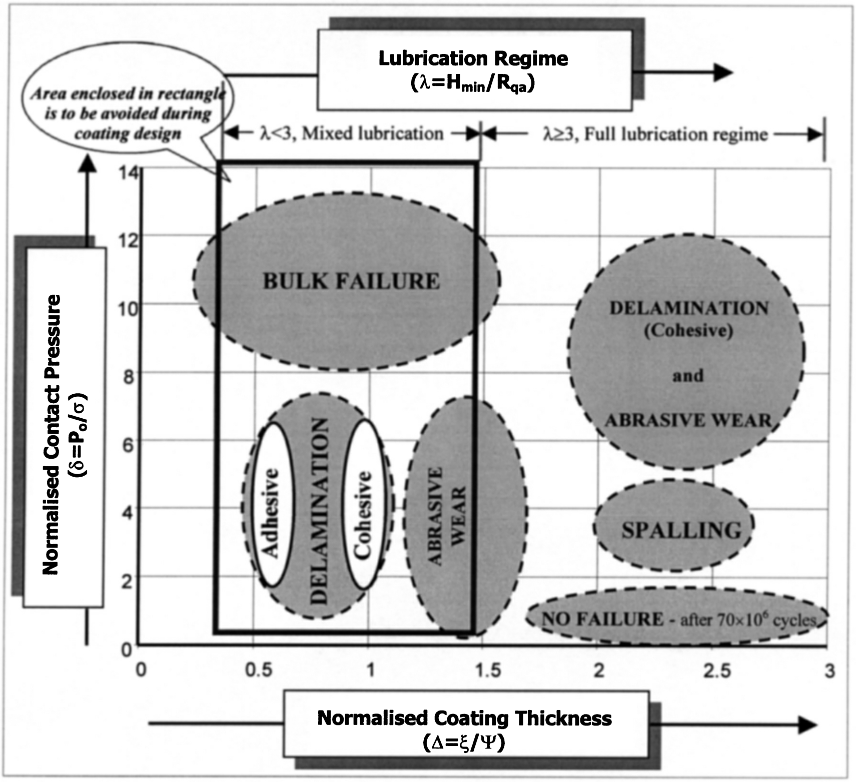

Figure 5, Wear map of WC-Co thermal spray coatings ($K_{IC} \geq 1.7$ MNm$^{-3/2}$) in rolling contact.