Fatigue Evaluation of Novel HVOF Spray Coated Al Bearing Alloys

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Abstract

The high velocity oxy fuel (HVOF) lining shows superior fatigue resistance to conventional roll-bonded (RB) linings of similar composition when compared in terms of local strain ranges experienced in the coatings. In terms of fatigue resistance of the bearing system, our simplified fatigue testing approach indicates that the HVOF coated system shows worse fatigue resistance, due to reduced constraint from the softer steel backing produced by the HVOF process (no work hardening of the steel occurs as it does during roll-bonding). The complex mechanics of the layered system are sensitive to bearing architecture (e.g. relative layer thicknesses) as well as the constituent materials' properties. The improved fatigue resistance shown by the HVOF lining has been linked to the very much finer Sn distribution improving fatigue initiation resistance compared with the RB lining, although short crack growth rates are somewhat worse.

1. Introduction

Currently the fatigue behaviour of automotive plain journal bearings requires further elucidation, since it is dependent on many factors. Loading via the hydrodynamic oil layer is both discontinuous and rapidly changing over the bearing surface, this, coupled with a multi-layer and multiphase material system, leads to complex fatigue behaviour. Previously, detailed experimental work has been carried out at Southampton University to characterise the initiation and early growth behaviour of fatigue cracks in conventional roll-bonded (RB) lining materials [1]. Bearing half shells contain several material layers: the lining material (typically a multiphase Al material, with Sn and sometimes Si phases existing as two discrete phase distributions) a thin interlayer of pure aluminium foil and a steel backing as shown schematically in Figure 1a. Studies of early fatigue initiation and short crack growth behaviour in conventional RB bearing lining materials have shown that multiple fatigue crack initiations occur associated with the softer Sn phase in Al-Sn systems, or the harder Si phase in Al-Sn-Si systems. The initial growth of these cracks is rapid and highly microstructurally dependent, the crack tip preferentially propagating through the Sn phase. Crack growth rate then drops or arrests entirely. Highly complex three-dimensional crack shapes evolve as the crack propagates along the interlayer between backing and lining, leading to significant shielding, as the crack grows from the softer lining towards the harder, stiffer steel backing [2]. Quantification of the "local" microstructure via novel image analysis techniques has been used to analyse crack initiation and early growth behaviour, indicating that the optimal fatigue resistant microstructure for this application will contain very fine Sn or Si/Sn particles [3]. HVOF spray coating processes offer a number of intriguing possibilities for this bearing application as very fine dispersions of Sn and Si can be achieved and the potential exists that functionally graded linings can be built up by altering the powder composition during spraying. This paper presents a comparison between the fatigue initiation and crack growth behaviour observed in similar Al-20wt%Sn lining alloys produced by both conventional roll-bonding techniques and the HVOF process.

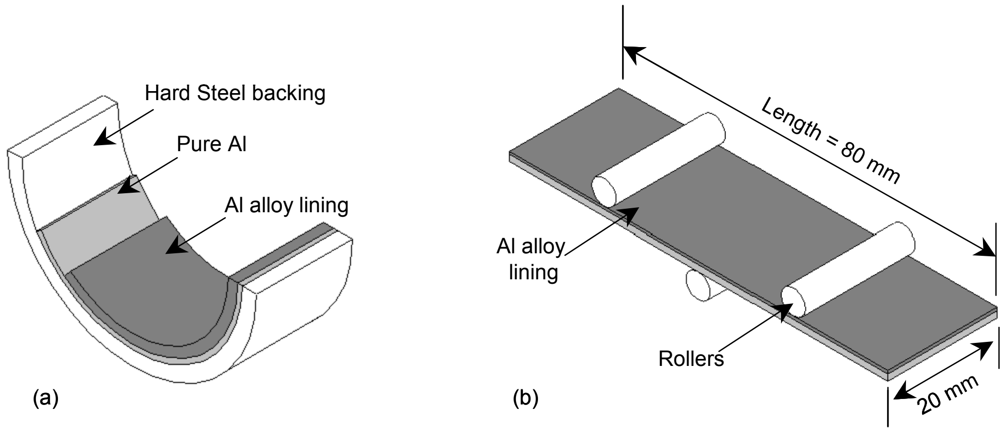

Figure 1: Schematic representation of (a) bearing geometry and (b) flat-strip fatigue set-up.

2. Experimental Methodology and Coating Characterisation

The two lining materials studied are based on AS16 (an Al-20wt%Sn-1wt%Cu) alloy and are produced by (1) conventional roll-bonding (RB): where the lining material is continuously cast, cut into billets, extensively cold worked to reduce thickness, roll bonded to the steel backing with an Al foil interlayer and annealed before finally being formed into bearings. (2) The second manufacturing approach uses the high velocity oxy-fuel (HVOF) spray coating process, followed by a 1 h 300˚C anneal in air, performed by Nottingham University. Full details of the HVOF process can be found in [4]. The two lining and backing microstructures are shown in Figures 2 a and c in the as-polished condition. Both linings are multiphase materials with the Sn existing as a distinct phase in both systems, although the distribution of the Sn can only be resolved optically in the RB material (Figure 2b), the Sn phase has been found to be in the size range 20-500 nm in prior TEM investigations of similar HVOF material [4]. In the RB material, the majority of the secondary phase is Sn, with the occasional darker grey phase being identified as $CuAl_2$ intermetallic. In the HVOF material, the far greater roughness of the steel backing/lining interface is evident, as is the lesser overall thickness of lining achieved in the spray coating process, some evidence of splat morphology can also be seen. For both manufacturing routes, the top surface would be ground away during bearing manufacture to produce an overall lining thickness of ~ 200μm. The higher levels of porosity visible towards the top of the HVOF lining would therefore be removed in the bearing manufacture process. Similar levels of grinding back were employed in preparing the fatigue specimens, which were also then given a polish of ~ 1μm to enable observation of fatigue crack initiation and early growth. The specimens used for the fatigue tests were bend-bar type flat-strips, produced in the condition immediately prior to the final bearing forming operation and were tested in a three-point bend configuration on a digitally controlled, Instron 8502 servo-hydraulic fatigue testing machine (± 50kN load capacity) as shown in Figure 1b. All tests were carried out in air at room temperature, at a load ratio of 0.1 and a frequency of 10Hz. To obtain the fatigue lifetimes, uninterrupted run out tests were conducted at a range of loads, whilst interrupted tests involving acetate replication of the polished flat strip bend bar surface gave detailed records of crack initiation behaviour for a particular stress level. Stress/strain levels for the replication tests were chosen to give appropriate testing lifetimes (<150 000 cycles) to allow the replication process to be used within reasonable testing times. A sample was considered to have failed when it had deformed by 0.5mm. Post-test the acetate replicas and failed samples were examined using optical and SE microscopy. An elasto-plastic finite element (FE) model was used to calculate the maximum lining surface stresses and strains. This assimilated test geometry, differences in layer thicknesses and used appropriate stress-strain curves: experimentally determined for the steel backing strips, and interpolated from hardness data for the lining materials [5]. The hardness measurements of the two coatings and the estimated σ_y and UTS values are given in Table 1:

Table 1: Comparison of hardness and estimated mechanical properties.

Lining material	Vickers Hardness (± St.Dev.)	Interpolated values	
		σ_y	UTS
RB	42.5 ± 3.4	54 MPa	196 MPa
HVOF	50.4 ± 2.8	64 MPa	233 MPa

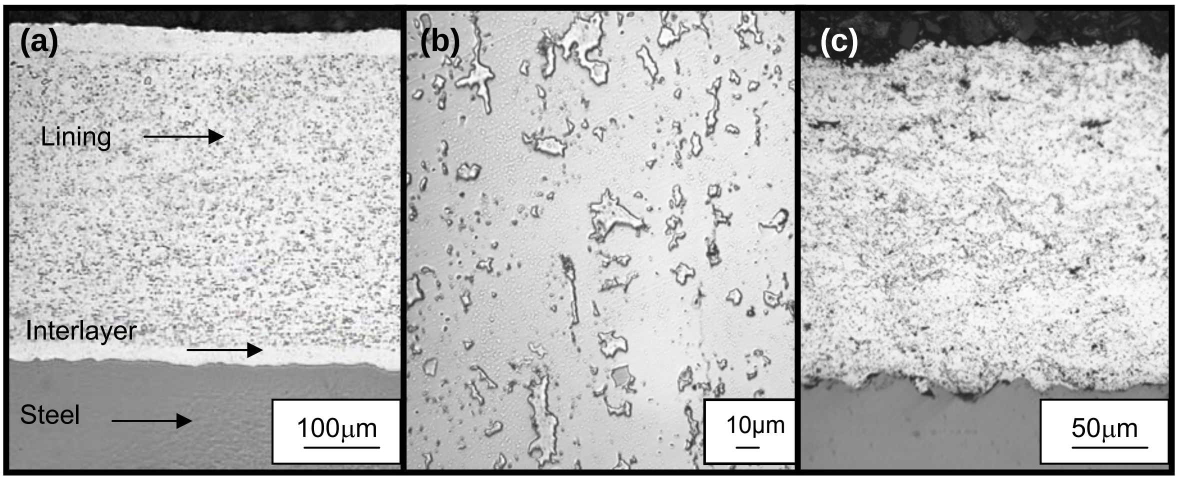

Figure 2: Polished sections showing (a) RB lining and steel backing (b) higher magnification view of the RB lining material (c) HVOF lining and steel backing, note rougher interface c.f. RB lining system.

3. Results

Figure 3a compares the lifetimes in terms of estimated plastic strain range. The steel backing for the RB lining (labelled AS16 in the figures) was considerably harder/stronger than the steel backing for the HVOF lining, so for similar applied loads, much higher stress and strain ranges were experienced in the HVOF lining c.f. RB lining (due to the lower constraint supplied by the HVOF steel backing). Crack growth rate analysis was therefore carried out at quite different maximum stress levels (64MPa for the RB lining compared with 103 MPa for the HVOF lining). Since surface crack growth rates have been compared on a ΔK basis this stress difference is to some extent accounted for, however the high levels of plastic strain render the LEFM assumption invalid, nonetheless, since a ΔK comparison is usually used in such short crack comparisons, we have presented our data in these terms. The HVOF lining shows improved fatigue resistance over the RB lining at high $\Delta\varepsilon$ levels, and comparable/slightly improved behaviour at low $\Delta\varepsilon$ levels.

In terms of short crack growth resistance however the two linings seem comparable, with somewhat faster crack growth rates observed in the HVOF lining.

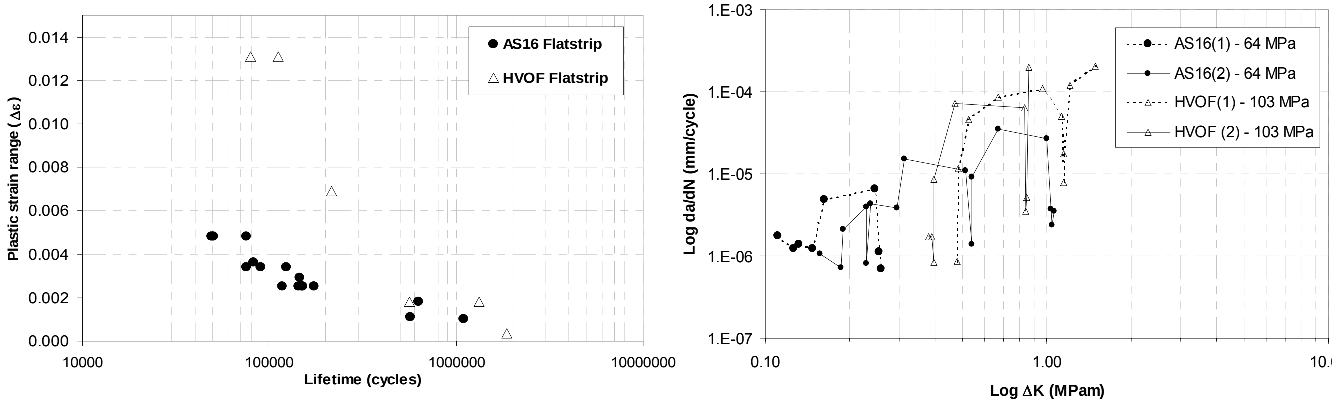

Figure 3: (a) HVOF and RB (labelled AS16) fatigue life-time comparisons in terms of estimated plastic strain range (b) crack growth rate comparisons in HVOF and RB linings. Note the difference in nominal maximum stress levels (64MPa for RB lining compared with 103 MPa for HVOF lining).

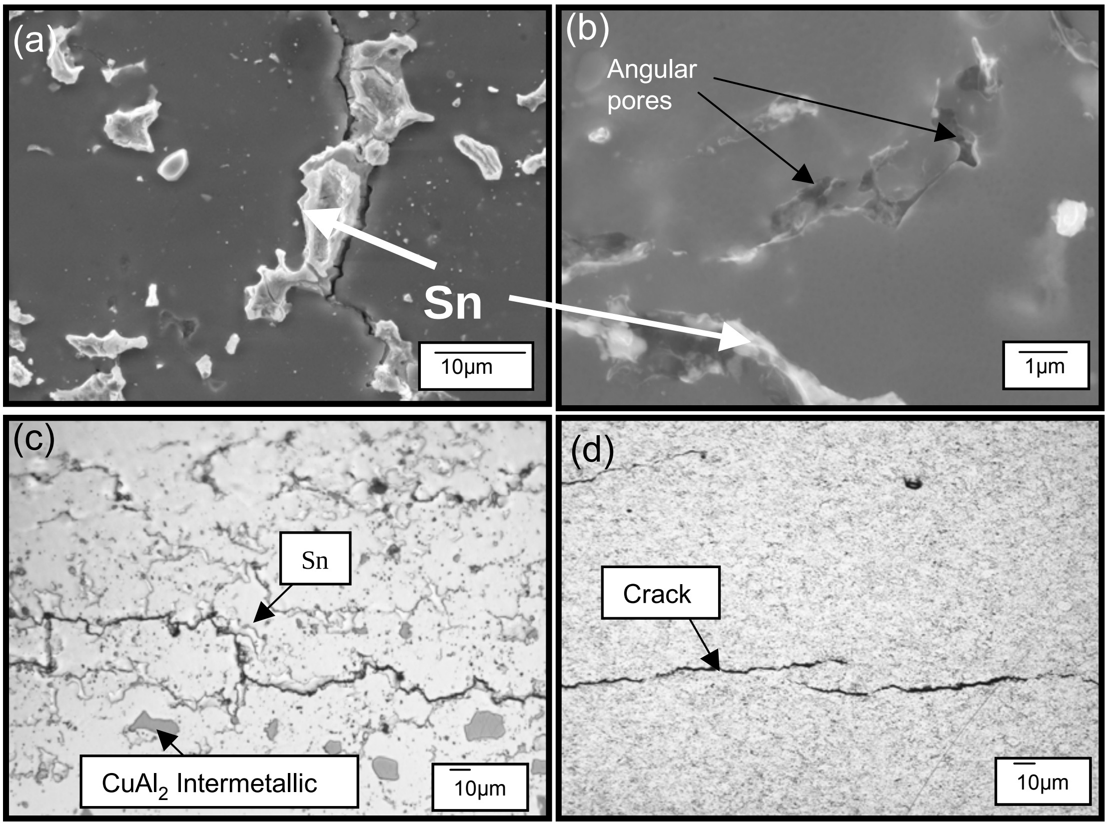

Figure 4: (a) RB lining, fatigue initiation observed by decohesion at large Sn particles (b) porosity observed in HVOF lining and very occasional large Sn particles (c) crack propagation in RB lining, note deviation of crack along the Sn-matrix interface (d) crack propagation in HVOF lining

Figure 4 shows details of the crack initiation and propagation mechanisms observed in each lining. The initiation sites in the HVOF lining were not associated with decohesion of large Sn particles as seen in the RB lining (Figure 4a) [3] but were associated with pores observed in the HVOF coating (Figure 4b). These pores had relatively high aspect ratios and sharp corners which appear to have initiated fatigue cracks. Propagation was quite different in the two linings, with more tortuous microstructurally dependent crack propagation along the coarse Sn phases observed in the RB lining (Figures 4c and d). The cracks in the HVOF lining were much straighter, however the degree of microstructural dependence is hard to ascertain from OM scales of resolution given the far finer scale of the HVOF microstructure. Crack coalescence occurred in both linings as multiple cracks initiated at these relatively high $\Delta\varepsilon$ levels/low lifetimes. The dominant cracks formed by such coalescence propagated through the lining and eventually caused sufficient deflection in the specimens to reach the criterion defined for failure. Sectioning of the failed linings revealed that significant crack deflection occurred as the dominant cracks propagated from the lining surface towards the steel backing. In Figure 5(a) the crack deflection parallel to the interface within the Al foil interlayer can be seen in the RB lining whereas in Figure 5(b) the deflection has occurred along the steel/lining interface. The cross-section of the major crack also indicates that macroscopically deflection occurs about the "splat" morphology that exists on a larger scale in the HVOF coating.

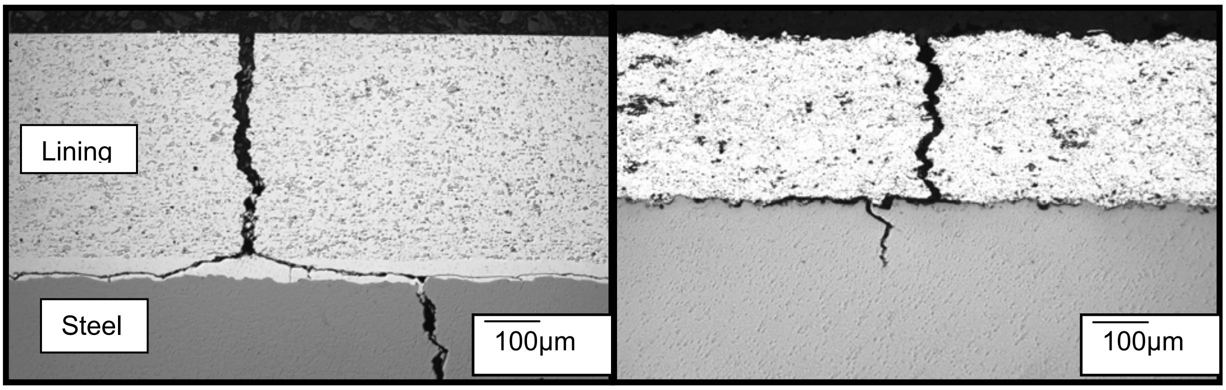

Figure 5: (a) Crack deflection perpendicular to the interface along the softer Al interlayer in RB lining system (b) Crack deflection along the interface in the HVOF lining. Note porosity in HVOF coating

4. Discussion

The rougher interface in the HVOF case is the result of the grit blasting required to ensure good adherence of the spray coating, however the interface integrity is clearly better in the RB sample. Crack deflection on traversing from a soft to a hard coating can be explained by the drop in driving force experienced at the crack-tip and in the case of a well-bonded interface the crack deflection is predicted to occur within the soft Al interlayer rather than at the interface, as observed in the RB lining [2]. In the HVOF lining the cracking of the interface indicates it acts as a weak path, but in both cases the very large scale deflections observed will give significant crack shielding and delay crack propagation into the steel backing. In bearings however it is the spalling off of sections of coating due to fatigue processes that needs to be guarded against, as this will cause seizure of the journal. The splat morphology within the HVOF coating can be seen to be of the order of ~20-30μm. As this is a relatively cool HVOF deposition process, the splat morphology can be discerned due to the presence of partial unmelts in the coating, the splat morphology affects the macroscopic crack propagation, offering preferential crack paths around the unmelt boundaries, where much larger Sn particles are occasionally found. The HVOF process has produced a harder coating and this has been linked to the very much finer Sn dispersions produced by this process in the majority of the coating [4]. The propagation of *short* cracks in the HVOF coating appears far less deflected than in the RB lining, where the coarser Sn particles (~5-10μm) act as preferential crack paths, giving increased crack path tortuosity and somewhat better crack propagation resistance (possibly due to increased crack shielding effects). Initiation in the RB lining has been shown previously [3] to occur at coarse, high aspect ratio Sn particles with their major axis aligned perpendicular to the tensile axis, due to the raised matrix hydrostatic stress in these regions. As such, the finer Sn particles in the HVOF coating were expected to be far less deleterious in terms of crack initiation. Indeed angular pores rather than Sn particles are now found to act as the major crack initiation features in these coatings, such pores have greater stress concentration at the pore tips which act as fatigue initiators. In terms of lifetime as a function of the local $\Delta\varepsilon$ levels experienced in the linings, the HVOF lining performed better than the RB lining. Since short crack propagation is similar if not slightly worse than in the RB system, it seems likely that this improvement is linked to delayed crack initiation, further work is planned to clarify this. However because of the reduced constraint from the steel backing in the HVOF system, the fatigue lifetimes in terms of applied load were much worse, indicating that the overall constraint of the bearing system as a whole will also have considerable effects on the fatigue resistance of the component. The lower strength of the HVOF steel backing is believed to be due to the lack of work hardening which the RB steel backing experiences during processing.

5. Summary and Conclusions

In direct materials comparison terms, the HVOF lining shows improved fatigue resistance over the conventional RB lining material which has been linked to an improvement in initiation rather than fatigue crack growth resistance. This is due to the considerable reduction in Sn particle size achieved in the HVOF process, which prevents fatigue initiation at Sn particles (as seen in the RB lining). Initiation in the HVOF coating occurs instead at stress concentration features of the angular pores present in the lining. Crack propagation rates are somewhat better in the RB lining due to increased crack path tortuosity as the crack seeks out the coarser Sn particles. The change in lining manufacturing process has also led to softer steel backings in the HVOF system, which provides less constraint to the lining, hence applying higher lining strain ranges for the same applied stress and hence shorter fatigue lifetimes for the HVOF system.

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