Edited by J.F. Nie, A.J. Morton and B.C. Muddle

The Potential of New Processing Routes in Al-based Plain Journal Bearings

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Keywords: Aluminium bearing lining, roll-bonding, high-velocity oxy–fuel spraying, fatigue strength

Abstract

Aluminium-tin alloy linings are used in modern plain journal bearings applications because they offer an acceptable balance between load-bearing capacity and fatigue resistance, in combination with conformability and embeddability. Conventionally processed bearings constitute tri-layer systems whose fatigue performance was found to be strongly dependent on relative layer properties and the micromechanics of the Al-lining. Novel HVOF processes have generated bi-layer systems with refined secondary phase distributions in the alloy lining and also opened up possibilities for varying mechanical properties through the lining thickness. The paper provides an overview of potential advantages that HVOF processing routes and new alloying possibilities might offer compared to conventional roll-bonding approaches.

1. Introduction

Half-shell bearings used in automotive main bearing and rod bearing applications operate in a complex environment which places conflicting demands on the bearing system. Strength is required for load bearing and resistance to fatigue damage, whilst at the same time “soft properties” impart conformability to accommodate system misalignments, as well as allowing embedment of debris. The bearing is also required to resist scuffing and seizure to the crankshaft if the hydrodynamic oil film were to become disrupted. This combination of properties is currently achieved using multilayer structures, which are categorised into two groups: 1. Tri-metal bearings comprising three layers; a steel backing, a layer of leaded bronze and a thin soft overlay, 2. Bimetal bearings comprising three layers; a steel backing bonded to a layer of aluminium bearing material by a thin pure aluminium layer.

Aluminium “bimetal” engine bearings are widely used in gasoline and diesel internal combustion engines for a range of half-shell bearings, bushes and washers. As mentioned above, the construction of these products is often actually a three-layer structure, consisting of a relatively strong steel backing, a thin “interlayer” and a bearing lining of an aluminium-tin alloy, Figure 1. The method of manufacture of the bearing shell is complex, and involves first casting a billet or continuously casting a coil of Al-Sn bearing alloy.

This is then roll bonded to the foil interlayer material, and then rolled further prior to final roll bonding to steel to generate the tri-layer structure. In addition, various heat treatments are used to generate the required microstructure. Blanks are pressed from the strip, features incorporated and then pressed into a half-shell shape, before final boring or broaching to the required wall thickness. The whole process of material manufacture is complex and requires careful control of parameters to ensure the correct bearing lining microstructure and properties, as well as bond characteristics between the layers. However, it does lend itself well to high volume manufacture and, with the correct process control measures in place, it is successfully employed throughout the bearing industry.

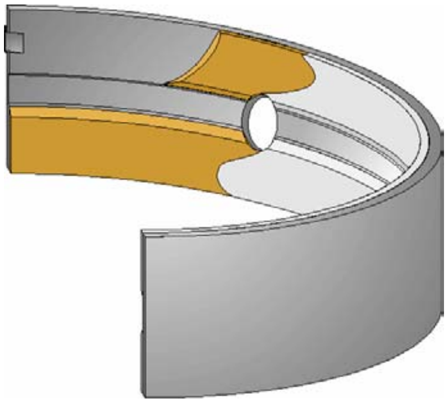


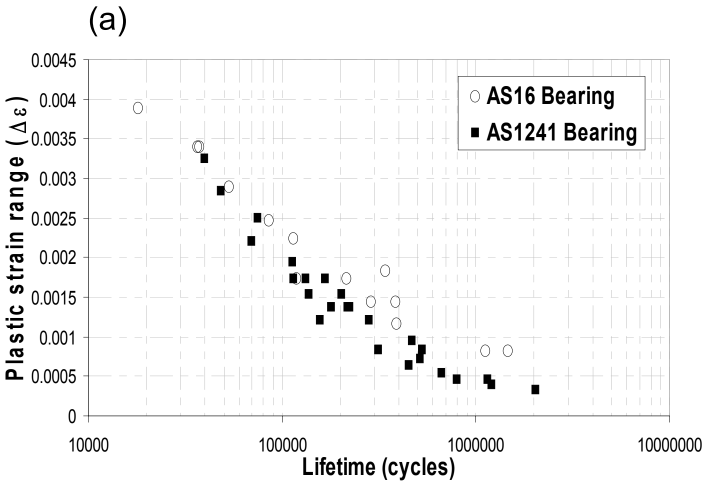
Figure 1: Schematic of typical shell bearing construction.

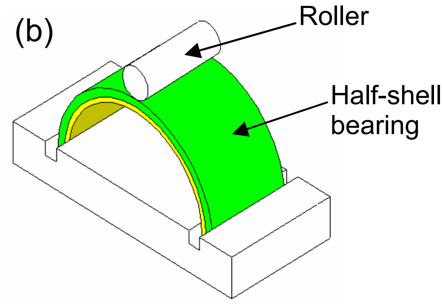
Half-shell bearings used in automotive main bearing and rod bearing applications operate in a complex environment which places conflicting demands on the bearing system. Strength is required for load bearing and resistance to fatigue damage, whilst at the same time “soft properties” impart conformability to accommodate system misalignments, as well as allowing embedment of debris. The bearing is also required to resist scuffing and seizure to the crankshaft if the hydrodynamic oil film were to become disrupted. This combination of properties is currently achieved using multilayer structures, which are categorised into two groups: 1. Tri-metal bearings comprising three layers; a steel backing, a layer of leaded bronze and a thin soft overlay, 2. Bimetal bearings comprising three layers; a steel backing bonded to a layer of aluminium bearing material by a thin pure aluminium layer.

Fatigue damage is not normally observed under typical normal operating conditions in an engine, as the bearing size, type and material are selected on the appropriate design load criteria, however it is necessary to evaluate fatigue resistance for new systems to continue to ensure this. This study concentrates on aluminium bimetal bearings, where tin is added in order to achieve the desired combination of properties. A typical bearing material would have a composition of Al-20Sn-1Cu (AS15). This material can be alloyed further to achieve higher strength for more demanding applications, for example Al-20Sn-1Cu-0.25Mn (AS16) and Al-12Sn-4Si-1Cu (AS1241).

Extensive fatigue testing of bimetal bearing systems has indicated the importance of both the relative mesoscopic layer properties [1] and the micromechanics associated with the secondary phases in the bearing lining itself [2]. The microstructure of commercial bimetal bearing alloys consists of a reticular structure of secondary phase particles of both silicon and tin, or tin alone, dependent on the alloy composition. Novel high-velocity oxygen fuel (HVOF) processes have recently been studied by Glacier Vandervell and at Nottingham University, and these provide the opportunity to greatly refine the tin and silicon distributions in bearing alloys. This novel approach to constructing a bearing lining also offers the opportunity for varying mechanical properties through the lining thickness. In choosing any manufacturing route there is a complex interaction between the soft, conformable characteristics desired and fatigue/strength requirements, alongside cost implications. The paper provides an overview of the relative advantages and disadvantages associated with conventional roll-bonding approaches, HVOF processing routes and the new alloying opportunities offered by this route with the concomitant changes in critical service properties.

2. Fatigue Assessment of Roll-Bonded Bearing Systems





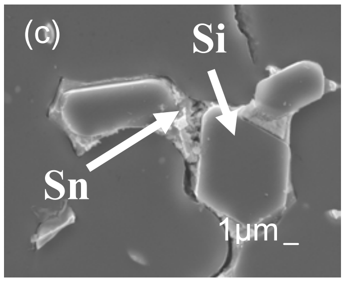


Figure 2: (a) $\Delta\varepsilon$ vs N_f data for AS16 and AS1241 bearing linings (b) three point bend testing of bearings (c) fatigue initiation at decohesion of Si particle in AS1241.

Figure 2a compares the $\Delta\varepsilon$–N_f data for conventionally produced roll-bonded bearing linings AS16 and AS1241. The linings are comparable in performance under these artificial testing conditions, with perhaps a slight improvement in performance at lower strain ranges (more representative of service conditions) for AS16. The half-shell bearings were tested in three-point bend as shown in Figure 2b on a digitally controlled, Instron 8502 servo-hydraulic fatigue testing machine (± 50 kN load capacity). All tests were carried out in air at room temperature, at a load ratio of 0.1 and a frequency of 10 Hz. The local strain ranges developed in the linings were estimated by finite element (FE) modelling of the half-shell geometry and it was found that the degree of constraint supplied by the steel backing during loading is strongly dependent on the relative layer thicknesses. The respective elastic-plastic behaviour of the steel backings and the conventional roll bonded linings were quite similar, although varying these properties and thicknesses markedly in FE simulations was found to alter predicted crack propagation behaviour significantly [1]. Once thickness differences were accounted for, the relative materials fatigue performance of the two lining alloys could be compared. The crack initiation and early growth behaviour were assessed through replication studies on interrupted flat strip tests (see section 4 for fuller experimental details); Figure 2c shows a typical fatigue initiation site at a large Si particle in AS1241. In AS16, in the absence of Si, fatigue initiation occurred by decohesion around large Sn particles. Refinement of these initiating particles is proposed as a mechanism to improve fatigue resistance [2].

3. High Velocity Oxy-Fuel (HVOF) Sprayed Bearing Alloys

The possibility of using a high velocity oxy-fuel (HVOF) thermal spray method to produce shell bearings on to a steel backing has been examined [3,4,5,6]. Two different fuels have been considered i.e. propylene as a gas and kerosene as a liquid, for the combustion process which provides the high temperature, high velocity gas stream into which the powdered bearing alloy is fed. A number of alloys based upon the Al-Sn system have been sprayed to form 200-400 μm thick layers on 2 mm thick mild steel sheet. During spraying, the steel sheet samples are mounted on a horizontal turntable and rotated with a tangential velocity of 1 ms^{-1} whilst the spray gun positioned ~300 mm away traverses the surface vertically at 5 mms^{-1}. Production trials with this form of processing have concentrated on the use of the liquid fuel gun as the atomised alloy powders (nominally 22-106 μm in size) spray more effectively to produce a dense alloy layer.

The composition range of specific interest for bearing materials is typically 10-20 wt% Sn. Consideration of the binary Al-Sn systems shows that in this composition range liquid can transform to solid via either a stable equilibrium phase diagram or a metastable equilibrium diagram. At low rates of cooling the equilibrium diagram gives the following solidification sequence:

$$L \rightarrow Al_{ss} + L \rightarrow Al_{ss} + \beta\text{ - Sn} \qquad (1)$$

The resultant microstructure is one of dendritic α - Al and interdendritic tin.

However, at sufficiently high cooling rates from the liquid phase it is possible to suppress the equilibrium reaction in favour of a solidification path determined by the metastable phase diagram. This gives the following solidification sequence:

$$L \rightarrow L_1 + L_2 \rightarrow Al_{ss} + L_2 \rightarrow Al_{ss} + \beta\text{ - Sn} \qquad (2)$$

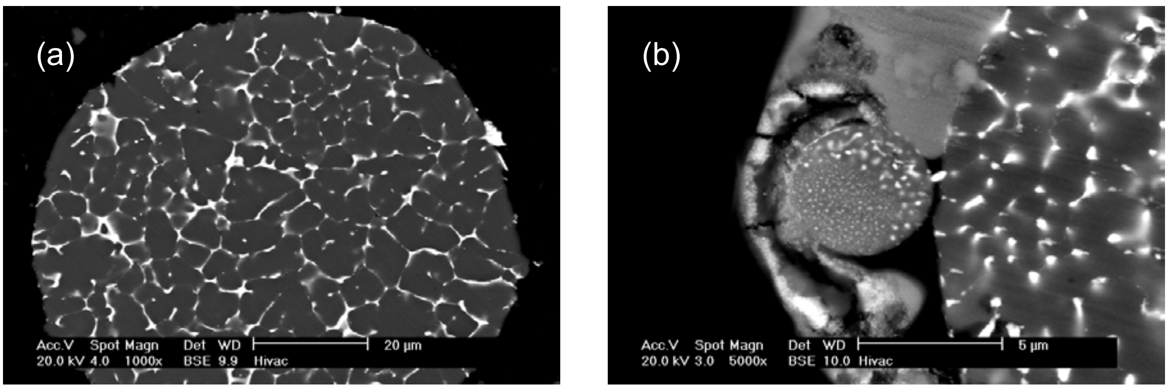


Figure 3: Scanning electron micrographs of Al-20% Sn particles (a) 80 μm particle with aluminium dendrites (dark) surrounded by interdendritic tin (light) (b) 8 μm particles with a fine dispersion of Sn in Al.

This involves liquid phase separation, $L \rightarrow L_1 + L_2$, the formation of Al_{ss} from L_1 and a eutectic reaction in which $L_2 \rightarrow Al_{ss}$ + Sn. In the gas atomised feedstock powder used for thermal spraying the vast majority of the powder particles exhibit a well defined dendritic microstructure indicative of solidification via the equilibrium reactions. However, fine powder particles, <10 μm in size, exhibit a microstructure with 50-100 nm sized tin particles dispersed in an α - Al matrix. These are shown in Figure 3 (a and b). This difference arises because in atomisation the finer particles are estimated to cool at ~ 10^6 K/s whereas coarser particles cool at around $10^3 – 10^4$ K/s.

The microstructures formed in sprayed deposits are complex because they are built up from the impact of both fully molten powder particles and partially molten powder particles. On impact, cooling rates in thermal spraying are estimated to be ~ 10^7 K/s. Thus, the HVOF-sprayed deposit comprises regions with finely dispersed, 20-50 nm sized, tin particles and other regions with micron sized Sn particles formed from the incompletely melted feedstock powder, see Figure 4.

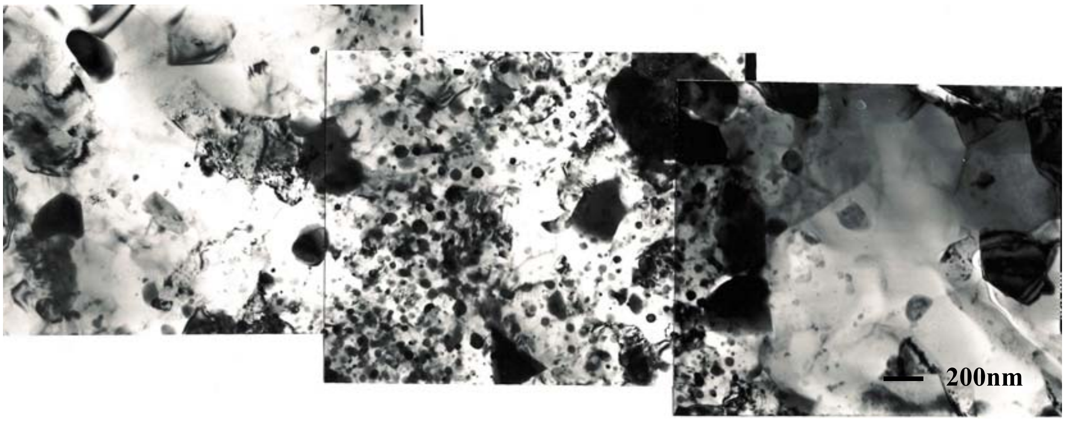


Figure 4: Transmission electron micrograph of an Al-20% Sn coating showing evidence of coarse aluminium grains (light) with large tin particles (dark) (on right and left of the picture) and a fine dispersion of tin particles in aluminium matrix (in the centre).

Other additions are made to the Al-Sn alloy i.e. Cu and Si. Copper additions influence the solidification process and promote coarser tin particles in the metastable reaction whilst silicon remains in solution. Subsequent heat treatment of the coating at 300°C promotes some coarsening of the tin particles and the formation of silicon precipitates. The action of coarsening tin particles improves the corrosion resistance of the alloy whilst the silicon promotes controlled hardening of the alloy. Hence a typical sprayed alloy may have a composition of Al-20 wt% Sn-1 wt% Cu-3 wt% Si.

4. Fatigue Comparison between HVOF and Roll-Bonded System

Figure 5a compares the $\Delta\varepsilon – N_f$ data for AS16, AS1241 and an HVOF produced AS15 coating. This data was obtained from bend-bar type flat-strips of steel backing and coating, with a polished lining surface, produced from the flat sheet condition immediately prior to the final bearing forming operation. These were also tested in three-point bend under the same conditions as the bearings [7]. In assessing the local strain ranges developed in the linings by FE, the degree of constraint supplied by the steel backing during loading was found strongly dependent on the steel properties (which are also affected by the cold work associated with the roll-bonding process) and the relative layer thicknesses. Thicker, stronger steel backings compared to relatively thin soft linings lead to lower strain ranges being experienced in the lining alloy, with an improvement in component fatigue lifetimes. In materials terms, the HVOF coating showed the best fatigue resistance, but because the HVOF mild steel backing experienced little significant work hardening c.f. the roll-bonding process, the HVOF flat strip showed the lowest lifetime in terms of applied stress ranges. More detailed description of the fatigue mechanisms observed in the HVOF lining can be found in the present conference proceedings [7]. In Figure 5b the short crack growth rates are compared on a ΔK basis: AS1241 appears to show the best short crack growth resistance, followed by AS16 and then the HVOF lining. This indicates that short crack propagation may not control overall fatigue resistance when compared on a $\Delta\varepsilon$–N_f basis.

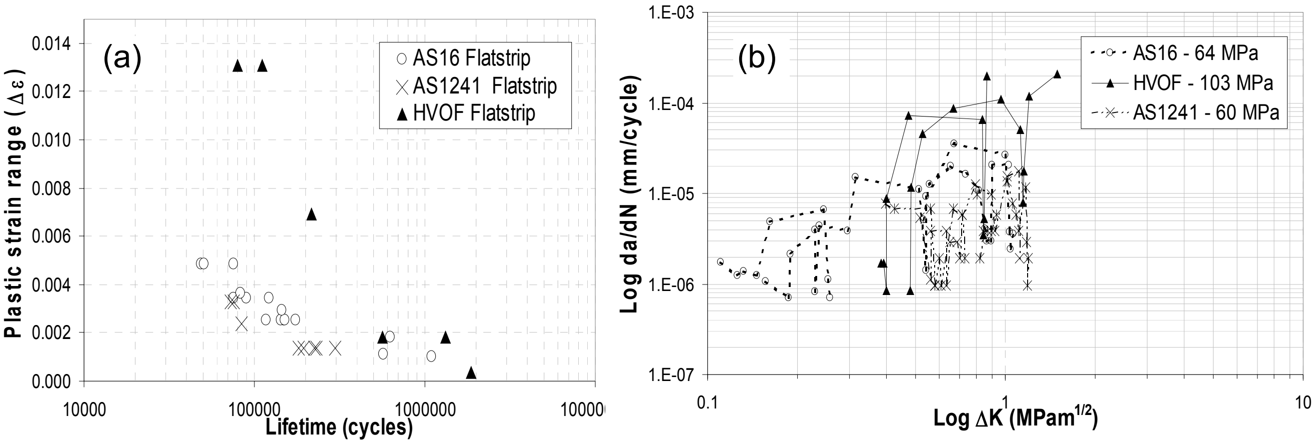


Figure 5: (a) $\Delta\varepsilon$ vs N_f data for AS16, AS1241 and HVOF flat strip linings (b) short crack growth rate comparison in AS16, AS1241 and HVOF flat strip linings.

5. Discussion

This work has successfully demonstrated the potential for HVOF as an alternative process for the manufacture of bimetal engine bearings. The ability to control the coating microstructure through processing parameters and alloying has yet to be fully exploited, but these both clearly present options for manufacture of higher strength and more fatigue resistant coatings. However, the fatigue analysis demonstrates that the overall performance of the part is dependent on more than just the properties of the coating, and further experimental work is required to confirm the optimum requirements in terms of the relative thicknesses of layers and their properties. Conventional processing methods for bimetal bearings offer a cost effective high volume process. The manufacturing issues and associated financial evaluation of implementing HVOF processes to generate a coating now need to be fully evaluated.

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