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**Notched Fatigue Testing of a
Hybrid Powder Metallurgy
Steel**

AJ Gant

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ABSTRACT

Fatigue testing of powder metallurgy (PM) steels, which can be considered to exhibit some ductility on both the macroscopic and microscopic scales, can be hampered by unpredictability of results due to inappropriate specimen configuration. This paper demonstrates the use of a V-notch specimen configuration in fatigue which produces fatigue data with a minimum of scatter. The effects of pressing pressure (and hence porosity) and heat treatment are investigated. The testing has been done as a proof of approach rather than a fundamental investigation of fatigue.

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1.0 INTRODUCTION

Powder metallurgy products are increasingly used as components subjected to cyclic loads and performance limitations associated with fatigue failure have arisen. Turbine discs or blades are typical low cycle fatigue applications for sintered materials. Over the past few years there has been greater concern about the fatigue properties of powder metallurgy products [1-5]. The results of research programmes obtained for powder metallurgy alloys are comprehensive. However, there is still a relatively wide gap between the knowledge of fatigue properties of pore free (wrought or cast) and of sintered materials. The concerns about the fatigue properties of powder metallurgy products are not always being addressed by currently available test methods since the data being produced often lacks consistency; hence there is a need to improve test methodology.

A common test used in the powder metallurgical (PM) industry for quality control and as a benchmark for mechanical property assessment is the transverse rupture (i.e. bend) test. Although a standard test is available [6], it is common to find material properties quoted according to an in-house procedure. Most commonly quoted are the results from three-point bend tests with the failure strength (σ_f) defined as the maximum fibre stress at fracture, and calculated from the formula which is based on linear elasticity:

$$\sigma = \frac{3PL}{3BW^2} \quad (1)$$

Where: P= rupture load

B=width

W=height

L/2= distance between inner and outer loading points at one end of the test piece.

The formula does not take into account any possible plasticity and assumes that failure of the bend specimen always initiates at the position of maximum stress at the surface. Results of conventional (i.e. un-notched) bend tests on PM steels have been reported for some time. However, there are several drawbacks to this apparently simple test. Precautions must be taken to ensure that the test is not influenced by surface conditions such as residual stress or the presence of unintentional stress raisers (e.g. from a poorly prepared metallographic surface). The use of a notched specimen configuration offers the possibility of reduced scatter in both static and fatigue tests due to the relatively small volume of material (i.e. at the notch) subjected to maximum applied bending stress, and also one in which through the use of carefully controlled preparation conditions, the variability in results in un-notched specimens due to defects introduced through sample preparation can be eliminated.

The use of notched specimens lends itself to the local stress concept. In contrast with other fatigue methodologies it has the following advantages:

- A design engineer will usually think more in terms of stresses than in terms of strains. Calculated stresses are compared with ultimate tensile stress or yield stress in the case of static design, and in the case of fatigue design, with the technical endurance limit

- The performance of load-controlled tests which deliver S-N plots for the nominal as well as local stress concepts is much easier and faster than the performance of strain-controlled tests.

Strain-controlled tests do give the possibility of life prediction of a component based on varying amplitudes, which is useful since fatigue service loads consist, in virtually every structural component, of varying load amplitudes that are a mixture of stochastic and deterministic components [7-9]. However, life prediction requires the use of a theory or hypothesis that yields good cumulative damage estimates and that accounts properly for the effects of non-zero stress and strain. In the case of porous powder metallurgy steels, life prediction using an empirical equation and damage summation (Miner's rule) has been found to be lower than that obtained experimentally [10]. Increasing porosity lead to an increase in the discrepancy between experimental data and those predicted.

For a broad application of the local stress concept, the use of S-N plots obtained only with unnotched specimens, mostly under axial and fully reversed loading ($R=-1$) is not sufficient, as components do not exist without notches, and loadings with mean stresses of $R \neq -1$ can occur too. Effects occurring in notches due to stress gradients should not be neglected for an optimum exploitation of the materials fatigue performance. Therefore, the idea of the local stress concept, to use data from tests with notched specimens is very similar to the local strain concept, however, it is superior in terms of including the effects of stress gradients and multiaxiality on fatigue strength and life.

The primary objective of this work was to evaluate the versatility of the notched bend format for performing static and fatigue tests to assess whether static failure and fatigue failure origins could be identified and measured.

2.0 TEST SYSTEM

The test system used was an Instron 8872 rig used in compression mode for the fatigue tests in an Instron 1197 rig for static rupture tests.

3.0 MATERIALS, TESTPIECES AND TESTS

Ancorloy 2 steel was obtained from Hoeganaes Corporation for the test programme and its composition is given in Table 1. It is a "hybrid" PM steel; i.e. it is manufactured from a prealloyed base steel with admixed additions.

The Ancorloy 2 material (FLN2-4005 in the new PMIF designation) is a hybrid alloy powder (prealloyed base with additions of elemental powders - in this case chemically bonded to the prealloyed base powder) that is designed to compete with the well established diffusion-alloyed powder of the same chemical composition. In addition to the difference in alloying method (hybrid versus diffusion alloyed), the fact that the Ancorloy material is based on a prealloyed powder increases its yield and ultimate tensile strength in the as-sintered condition compared with that of the as-sintered diffusion-alloyed material - when the two have the same sintered carbon content. The hybrid alloy (Ancorloy 2), while having higher tensile strength would have slightly lower tensile ductility and very slightly lower impact energy. If the sintered carbon content of the Ancorloy material is adjusted (lowered) so that the yield strength of the diffusion-alloyed material is matched, then the two materials will have comparable

tensile ductility. For heat treated materials (quench-hardened and tempered) the hybrid alloy has equivalent tensile and impact performance to the diffusion -alloyed material ; both materials will have tempered martensitic microstructures. The difference between the two materials would be seen in their different hardenability; the hybrid alloy that is based on a prealloyed powder will have a greater hardenability compared with the diffusion-alloyed material that is based on an iron powder. The diffusion-alloyed materials are well established in the marketplace. The fatigue data for the Ancorloy 4 based material (FLN4-4005) that is published on the MPIF web site indicates that, for a given density, the hybrid material has better fatigue performance than the equivalent diffusion-alloyed material. Data for the Ancorloy 2 based material (FLN2-4005) that has just been approved for ballot by the MPIF Standards Committee shows that the same holds true for this material also.

Ancorloy 2 is an engineered binder-treated premixed material designed as a high-performance alternatives to malleable and ductile cast iron materials. Hoeganaes introduced its Ancorloy family of products in 1999 with the launch of Ancorloy 2 and Ancorloy 4. The former is a premixed product equivalent in composition to Distaloy 4600A (a well established diffusion alloyed steel). Diffusion alloying and binder treatment are alternative methods that have essentially the same technical objectives. These are to improve the inherent compositional homogeneity of the resultant powder without adversely effecting its other processing characteristics, especially compressibility. Consequently, as applied to the manufacture of press-ready premixes, they offer many of the same advantages. For example, compared with compositionally similar premixes made according to conventional practices, these typically include: improved powder flow; minimally equivalent and frequently better green properties; and decidedly improved dimensional stability after sintering [11,12]. The two processes accomplish their aims and produce the indicated improvements in much the same way. Basically, they each effect superficial bonds between the particles of the base powder and those of the affected admix ingredients. However, as their respective names imply, they employ very different means to do this. Diffusion alloying is a pyrometallurgical process and may involve chemical and/or metallurgical reactions in addition to bonding. Binder treatment, on the other hand, is primarily a simple gluing process and had little if any potential for either chemical or metallurgical effects beyond those of bonding. Thus, in spite of the fact that the two methods accomplish their aims in much the same way, the underlying mechanisms are intrinsically very different. Consequently there is no guarantee that their application as a general matter will necessarily lead to the same results. For example, diffusion alloying is not applicable to duplicate the properties of binder treated premixes that simply add carbon as graphite and/or phosphorous as Fe_3P . The difficulty in the first place being the unwanted formation of an intermetallic compound and in the second, the decomposition of one. Until recently, binder treatment has also been unable to duplicate the properties of the premix compositions based on the diffusion alloyed grades according to MPIF Standard 35, (i.e. also known commercially as Distaloy AB and Distaloy AE).

The Ancorloy products represent a significant development in metal powder technology; they offer fabricators opportunities for expanding into new applications, especially in the automotive industry which uses a considerable amount of cast iron products [13]. The initial focus will probably be on applications such as ring gears, parking brakes, carriers, and high-performance bearing caps, as well as potential diesel applications.

The Ancorloy products all require high-temperature sintering of up to 1260°C. Sintering at lower temperatures will not provide the broad range of high-performance characteristics offered by the products [13]. Primary property improvements will be realized in ultimate tensile strength (UTS), yield strength and elongation, but it is the combination of the extremely high strength with good elongation that allows the materials to match malleable and ductile cast iron performance characteristics.

The Ancorloy products are a derivative of Hoeganaes' 'ANCORBOND' processing technology for producing binder-treated premixed metal powders. The process overcomes the problem of product segregation, improves product flow and die fill, and provides consistent sectional densities, weight distribution, and alloy homogeneity. These advantages have helped parts makers to improve production rates and have virtually eliminated part- to-part variability during production [13].

Six batches of Ancorloy 2 steel with identical compositions were procured for the test programme as indicated in Table 2. The first three indicated (EHY2, EHY3 and EHY4) have been tested in the as-sintered condition and are identical in composition, but have been pressed at different pressing pressures, these being 415, 550 and 690 MPa respectively. The latter three grades (EHY5, EHY6 and EHY7) have been tested in the quenched and tempered condition and are identical in composition with the first three grades, but have again been pressed at different pressing pressures, these again being 415, 550 and 690 MPa respectively. These samples had been austenitised at 870 °C, quenched into oil at 60 °C and tempered in a nitrogen atmosphere for one hour at 250 °C. Microstructures of the three heat treated grades are shown in figures 1-3 respectively. Tempering after sintering is not a common practice. However, given the moderate cooling rates typical of an average sintering furnace, highly alloyed molybdenum containing steels such as the present grades frequently precipitate low temperature transformation products; austenitising and quenching prior to tempering is a means of eliminating these phases [14].

Testpieces were wire electrodischarge machined (EDM) from larger blocks of material to a nominal, rectangular, 5 mm × 2 mm × 45 mm size. These were then lightly ground using a diamond wheel to remove EDM residues and ensure parallel dimensions (to ± 0.01 mm). A central 45° vee-notch was then ground in the 2 × 45 mm face, being 1 mm deep and having a tip radius of 0.1 mm.

The following test types were examined:

- Static load
- Fatigue load

Six sets of 20 specimens were initially tested, the first five of each being tested in static bending. The static tests were undertaken on a Instron 1197 rig with a 100 kN load cell. Transmission of the load from load cell to specimen was by means of compression platens and a four point bending jig with no articulation. The inner span was 10 mm and the outer span 30mm, the bending being imparted to the specimen by means of hardmetal rollers (fixed in the lateral plane, but free to roll); see Figure 5. The machine was used under displacement control at a rate of 0.5 mm.min⁻¹ and the specimen loaded until rupture occurred. Precautions were taken to avoid post-rupture damage in the test rig by means of rubber strips under the tensile face of the bending jig.

Fatigue tests were undertaken on an Instron 8872 using the same bending jig as the static tests. Fatigue tests were undertaken using an R ratio equal to 0.1 and at a frequency of 10 Hz. The maximum applied tensile bending stress applied was dependent on the mean rupture stress determined from the static tests; initial fatigue tests were conducted using a maximum applied tensile bending stress equal to 95% of mean static rupture stress for both the as-sintered materials and the heat treated materials, with decrements of 5% being applied in subsequent tests in order to build up S-N plots for the respective materials. Up to 15 specimens were used in order to construct the S-N plots. The runout condition was arbitrarily assigned as being 10^7 cycles.

Subsequent tests were undertaken to determine the effects (separately) of a post-machining annealing treatment (200°C for one hour in air followed by a furnace cool to ambient temperature) and the effect of notch orientation. The effect of the former is shown in Figure 10 and the latter in Figure 11. In the case of notch orientation it should be noted that the results illustrated in Figures 6-8 are for the notch axis perpendicular to the compaction (i.e. pressing) direction.

4.0 RESULTS AND DISCUSSION

Initial static tests

Five samples of each material were ruptured in four point bending as outlined above. The mean local notch root strength data are outlined in Figure 4 (stress concentration factor at notch root = 3.82); these were used as a basis for the fatigue loading regimes for each batch of samples and the samples were retained for fractographic examination.

Fatigue tests

It can be seen from Figure 6 that all the materials under investigation exhibited S-N behaviour with little scatter (compared with other more conventional test methods such as rotating bending or alternating tension [15]). Also illustrated are the static results (arbitrarily assigned a value of 1 cycle on the x-axis due to the log scale). Figure 6 shows a general improvement in fatigue behaviour with increased pressing pressure and heat treatment. Figure 7 shows that in the case of the as-sintered materials, that those samples pressed at 690 MPa gave a superior fatigue performance to the other batches. There was also little difference in terms of fatigue performance between the samples pressed at 415 MPa and those pressed at 550 MPa in the as-sintered condition; see Figure 8. Figure 9 shows results for two WC-Co hardmetals, ASP30 high speed steel and the heat treated Ancorloy which had been pressed at 690MPa and demonstrates the wide applicability of the test method.

Runout usually occurred at 30-60000 cycles and at a maximum cyclic stress of the order 30-40% of the static bend strength. In general the fatigue strength of PM materials is correlated with the ultimate tensile strength, by computing the fatigue ratio; the figure of

0.3-0.4 found in the present work using static bend strength closely matches the ratio found in the literature using [16-19]. For conventional wrought steels a higher value of 0.4-0.5 has been found [20]. The lower fatigue in PM materials can be attributed to the presence of porosity. Correlating fatigue strength with static bend strength may be more appropriate than correlating it with ultimate tensile strength, since in the case of the latter, it is really a measure of large-scale macroscopic damage that takes place at relatively large applied stress or plastic strain. Fatigue damage, on the other hand, is more complex and typically takes place at much lower applied stress by localised plasticity at defects in the material.

Figure 10 shows the fatigue performance of the 550MPa pressed and heat treated Ancorloy 2 with and without a post-machining anneal prior to the commencement of fatigue testing. It can be clearly seen that there is no detectable change in performance due to the annealing heat treatment. Figure 11 shows the fatigue performance of the 690 MPa pressed and heat treated Ancorloy2 with the v-notch machined both parallel to and perpendicular to the compaction direction. Again, there is no tangible effect of changing the specimen orientation when tested in fatigue.

Fractography was conducted on the specimens (both static bending and fatigue) initially by optical microscopy to try to identify the position of the failure-initiating region. Grazing incidence illumination [21] was also used where necessary to aid identification; however it was impossible to identify the fracture origins with any certainty. Detailed fractographic examination was conducted using a Hitachi 6400 field emission scanning electron microscope (FESEM), but again failure origins could not be identified; the fracture mode in all cases was ductile rupture; see Figures 12 and 13. Fatigue fractography provided additional insight into the influence of microstructure on fatigue damage. Figures 12 and 13 show the fatigue fracture surface of the material pressed at 690 MPa and heat treated. The fracture surfaces show localised dimpled rupture, evidence of void nucleation and coalescence in the sintered necks bonding particles; i.e. a cyclic ductile fracture mechanism was active [22], with each neck failing as an individual microtestpiece under local plane stress conditions [6]. This is a common fatigue mechanism in low alloy PM steels. However, other features such as plastic tearing (striation formation) [22-25] were not seen. A possible explanation for the lack of striation formation is that the cyclic stresses experienced (i.e. the local value of ΔK) were too large for their formation to occur [25]. Other possible failure mechanism which low alloy PM steels can experience are static shear failure, where the local shear stress approaches the yield shear stress. This type of fracture occurs where the crack front encounters an unfavourably oriented particle [22]. Also, static ductile failure can occur where the neck ligament is unable to support the applied load; however neither of these features were seen in the fatigue fracture surfaces examined in the present study.

% Ni	% Cu	% Mo	% Mn	% C	% Fe
1.76	1.49	0.52	0.16	0.49	balance

Table 1: Ancorloy 2 composition (after sintering).

Code	Pressing (MPa)	Pressure	Heat Treatment
EHY2	415		As-sintered
EHY3	550		As-sintered
EHY4	690		As-sintered
EHY5	415		Quenched and tempered
EHY6	550		Quenched and tempered
EHY7	690		Quenched and tempered

Table 2: Steels tested showing pressing pressures and heat treatments.

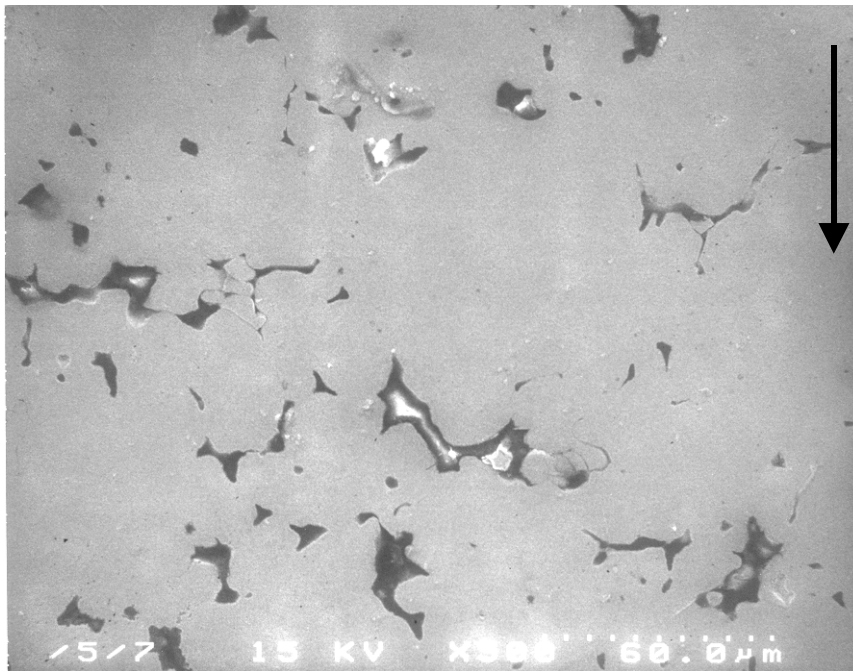


Figure 1: Microstructure of Ancorloy 2 pressed at 415 MPa, quenched and tempered (EHY5). Arrow indicates pressing direction.

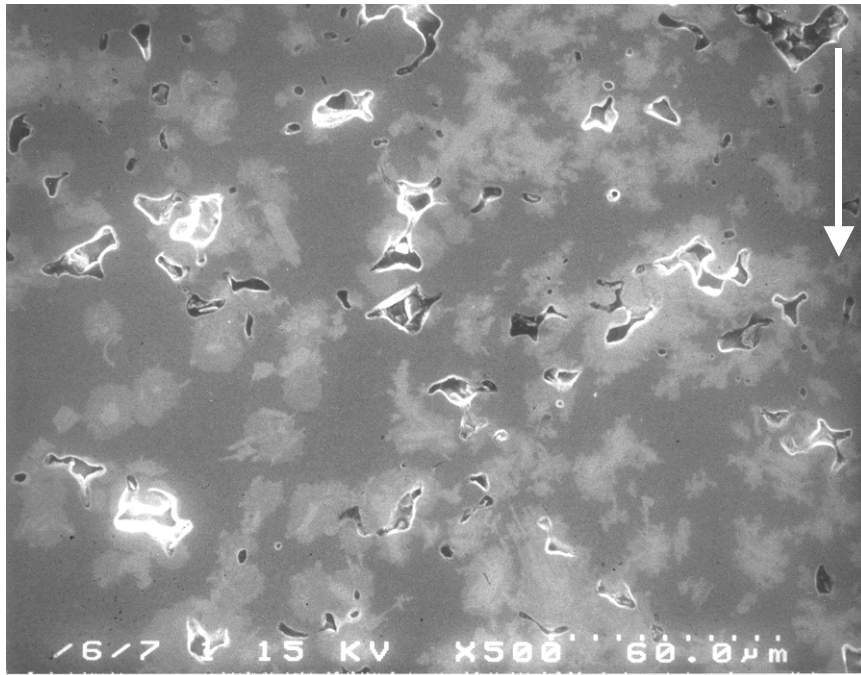


Figure 2: Microstructure of Ancorloy 2 pressed at 550 MPa, quenched and tempered (EHY6). Arrow indicates pressing direction.

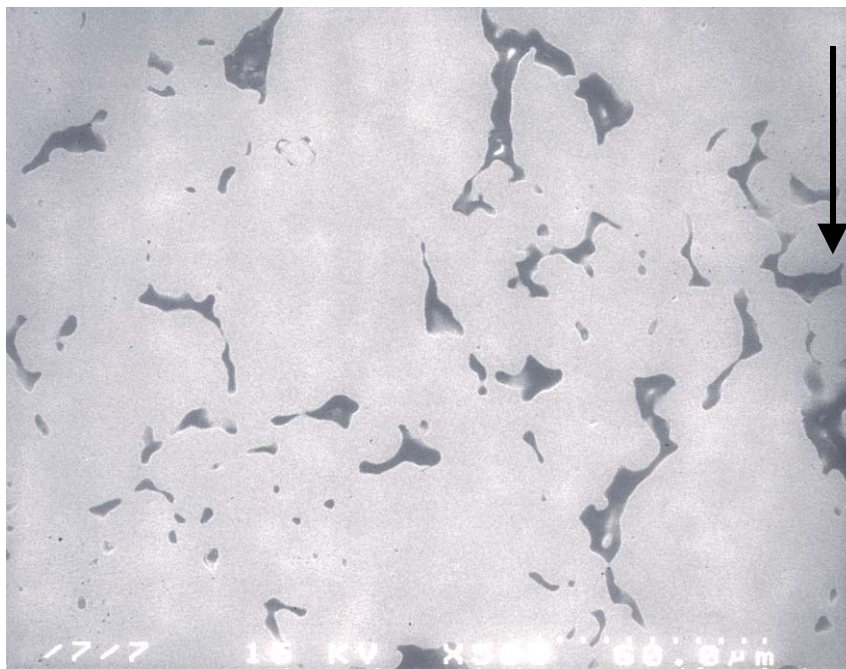


Figure 3: Microstructure of Ancorloy 2 pressed at 690 MPa, quenched and tempered (EHY7). Arrow indicates pressing direction.

Test Type	Load Rate	Frequency	R ratio	Load
Static	50Ns ⁻¹			To rupture
Fatigue	According to regime	10Hz	0.1	Peak load: 95% of static, in decrements of 5%

Table 3: Outline of test regimes.

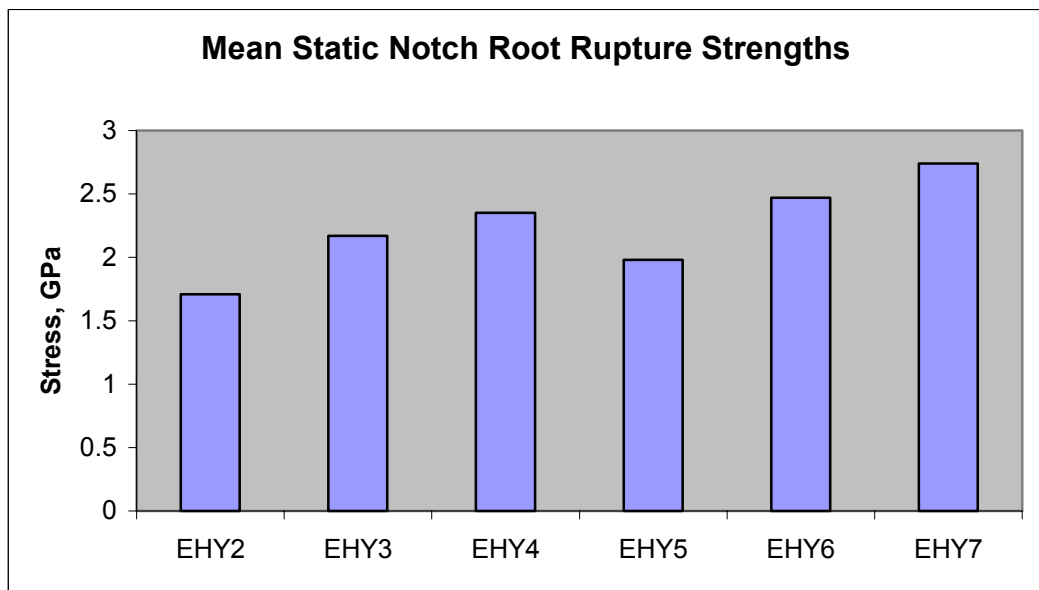


Figure 4: 4-point mean notch root rupture stresses used to determine stress regimes in fatigue.

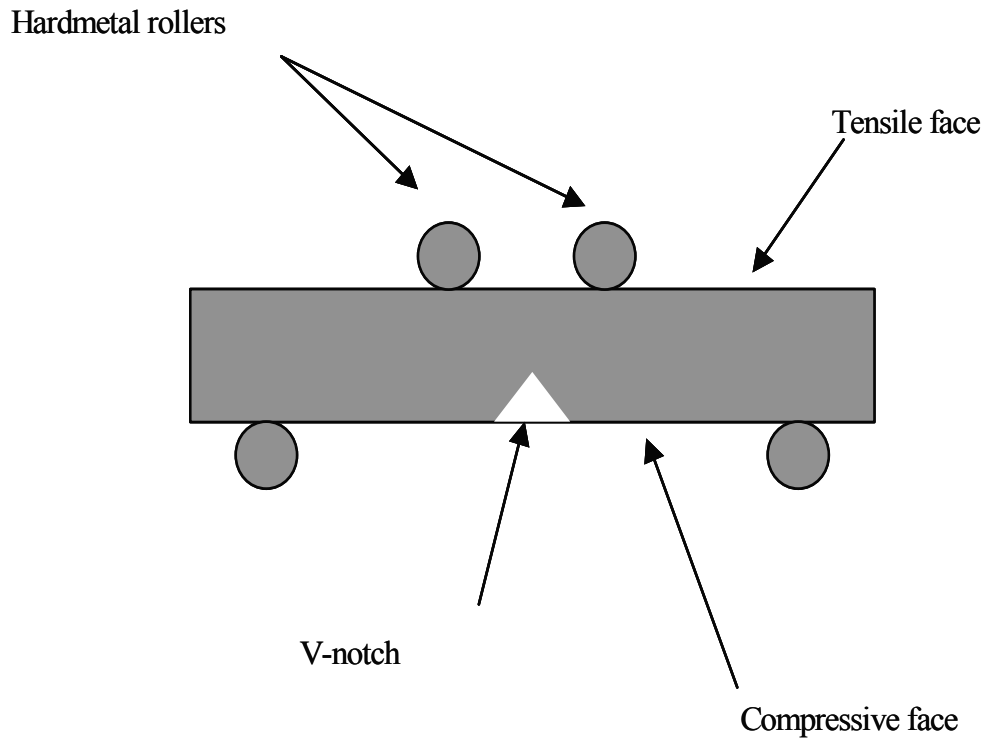


Figure 5: Schematic diagram of specimen configuration (both for static and fatigue tests).

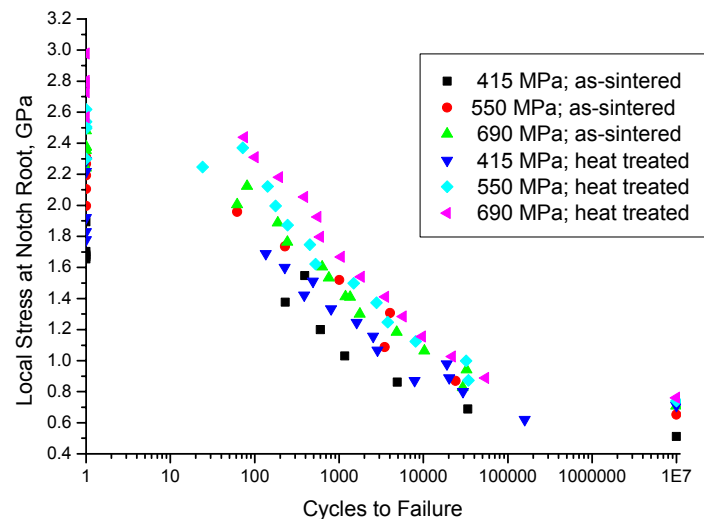


Figure 6: Summary S-N plot for all PM steels investigated

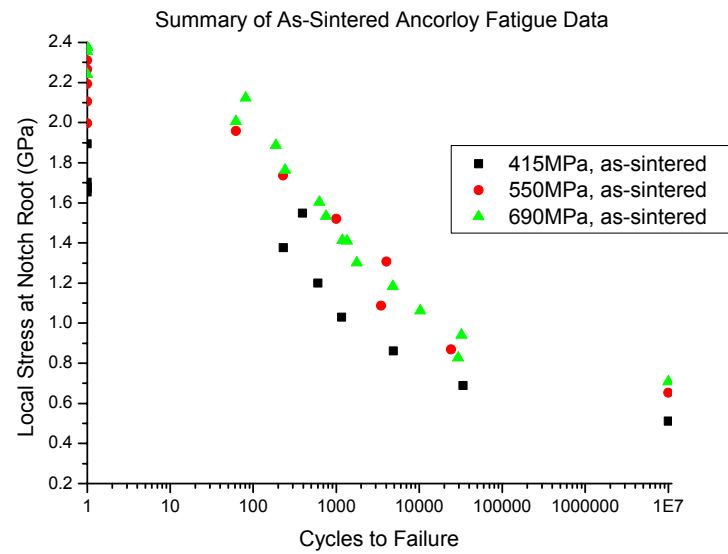


Figure 7: Summary S-N plot for as-sintered Ancorloy 2.

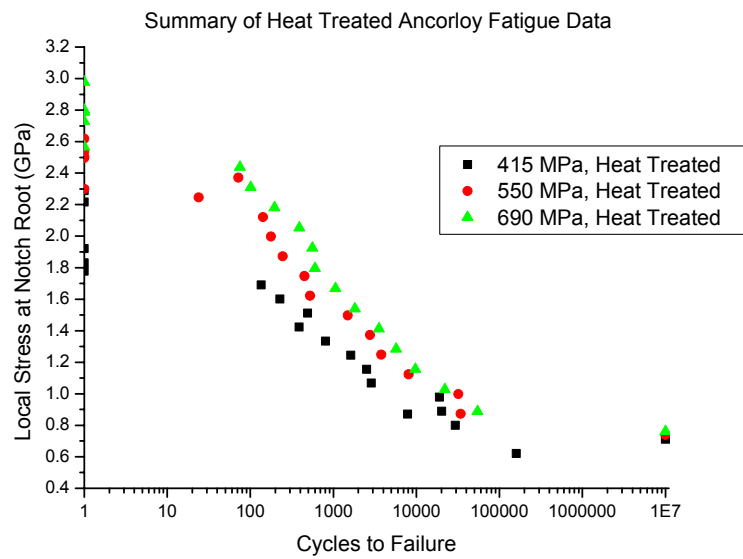


Figure 8: Summary S-N plot for heat treated Ancorloy 2.

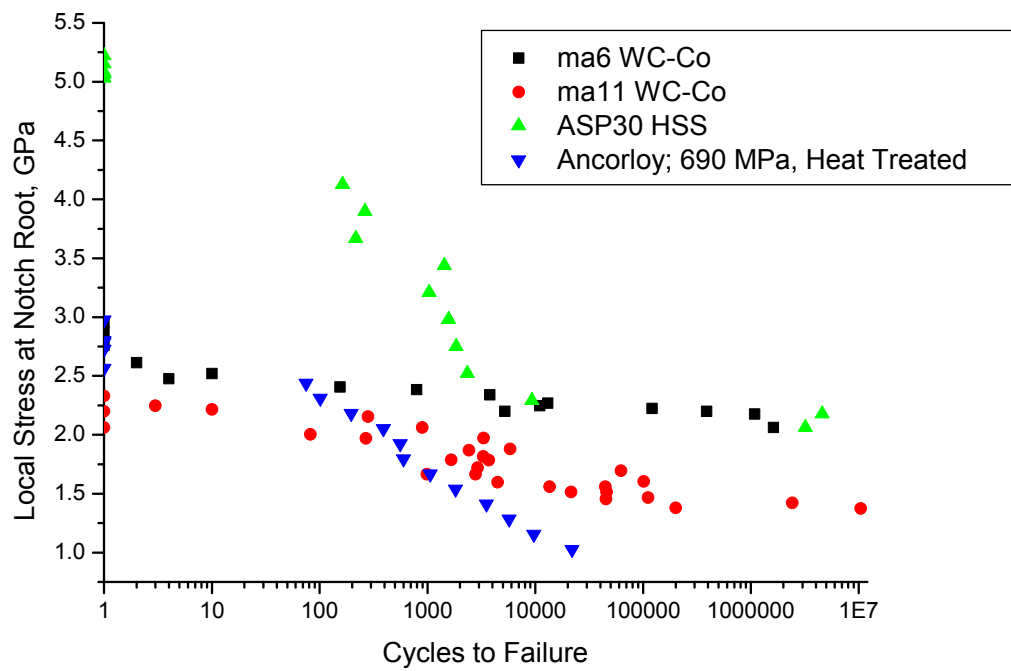


Figure 9: Summary S-N plot for hardmetals, ASP high speed steel and Ancorloy 2.

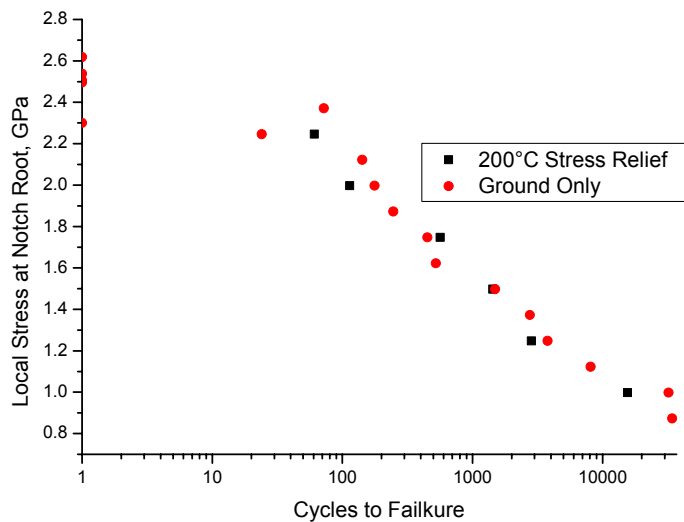


Figure 10: Comparative fatigue performance of Ancorloy 2 (550 MPa compaction, quenched and tempered) with and without post-grinding stress relief treatment.

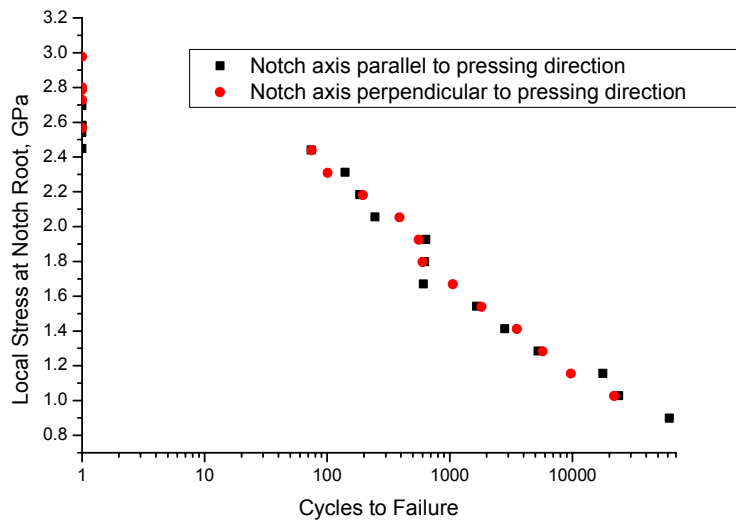


Figure 11: Effect of notch orientation with respect to pressing direction on fatigue performance of Ancorloy 2 (690 MPa compaction, quenched and tempered) .

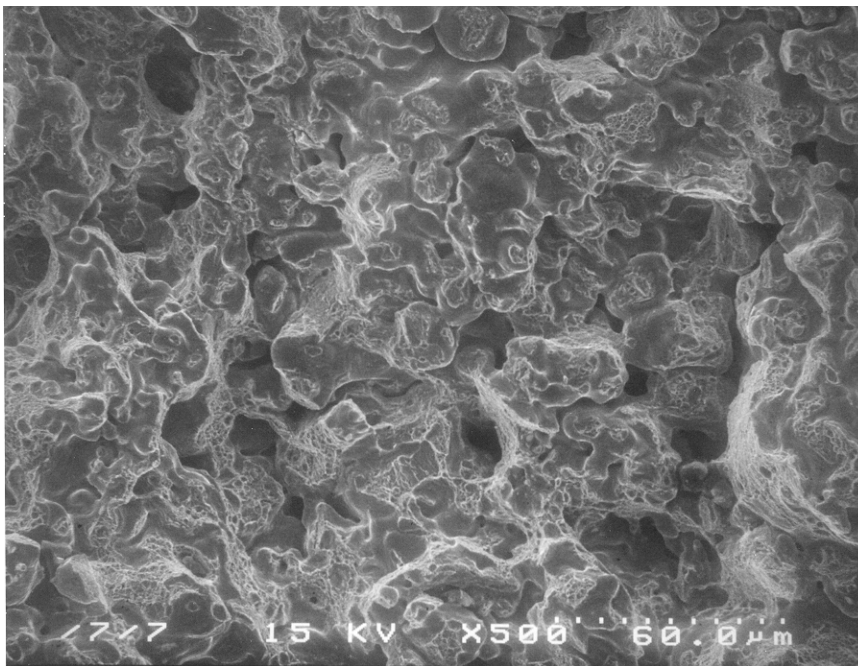


Figure 12: SEM fractograph of fracture surface of Ancorloy 2 pressed at 690 MPa and heat treated; immediately below the notch root.

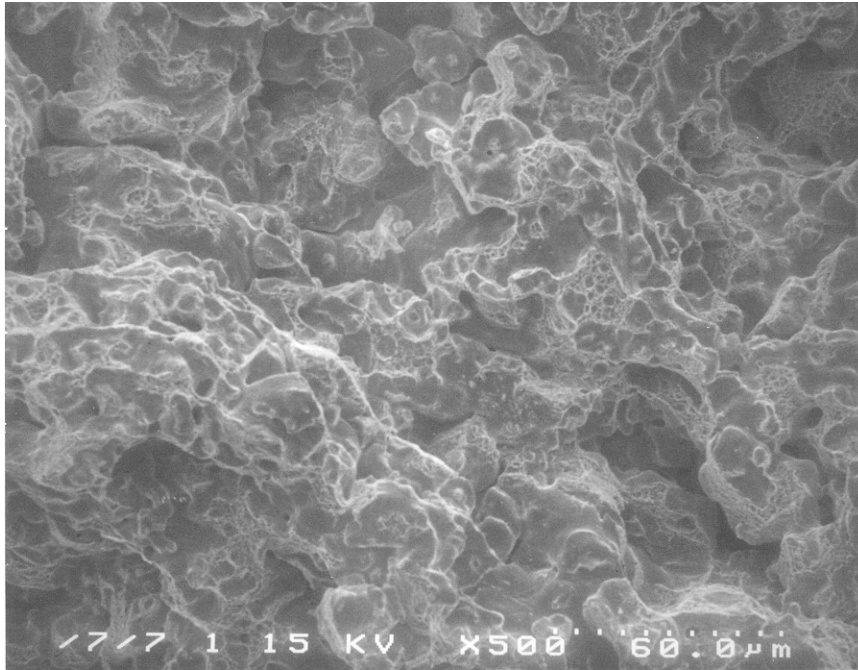


Figure 13: SEM fractograph of fracture surface of Ancorloy 2 pressed at 690 MPa and heat treated; immediately below the compression face of specimen.

5.0 CONCLUSIONS

- a) All materials show S-N behaviour, which has considerably less scatter than other methods; thought due to microstructure-initiated failure at or below the notch root.
- b) In terms of the S-N behaviour, there was an improvement in behaviour with increased pressing pressure and heat treatment (vs. as-sintered data)
- c) An endurance limit in fatigue was shown by all batches of Ancorloy 2 tested.
- d) The V-notch fatigue configuration has shown itself to be a quick and cheap method of assessing the fatigue performance of a range of PM materials.
- e) The test method has been able to discriminate between materials made using slightly different processing variables.

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