Measurement Note

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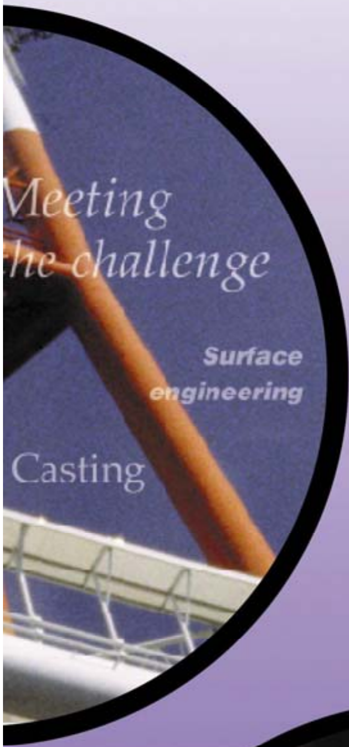
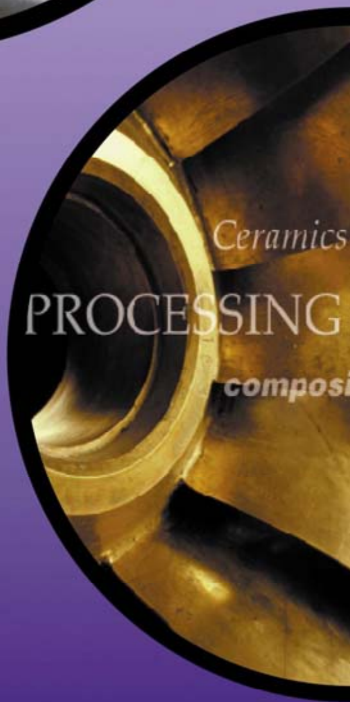


A method for high-temperature fatigue testing of hardmetals and PM materials

Hardmetals and ferrous PM products are often used at elevated temperatures, but there are very few data on fatigue life available because of the expense of undertaking such tests in a conventional way.

This Measurement Note describes the use of the notched flexure method and its use in fatigue testing to elevated temperatures. A protective heated enclosure has been designed, constructed and tested. Two grades of hardmetal with different room-temperature fatigue characteristics have been subjected to fatigue testing at 300 °C and 500 °C. At 300 °C, the materials have significantly greater fatigue life than at RT or 500 °C.



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Introduction

Many of the applications of hardmetals and hard PM products are at temperatures significantly above room temperature, exploiting their unique properties. Examples include forming tools, cutting tools, valves, and rolls. However, the database on material properties at use temperature is rather poor owing to the cost and difficulty of undertaking testing at elevated temperatures. This lack of data is hampering to designers and material specifiers because significant allowances have to be made to safeguard against suspected temperature effects.

Many different kinds of test method have been used to investigate the fatigue behaviour of hardmetals including fatigue crack growth, compression, tensile, S-N and contact fatigue modes. A good survey of the literature for fatigue crack growth type tests can be found in the recent paper by Llanes *et al.* [1]; while the most developed S-N method in recent years has been that applied by the Erlangen group [2, 3] to establish a fatigue life for different hardmetals. They devised a test method that uses a small area cross-section of test-piece to minimise the likelihood of fatigue initiation at gross defects. Both testing methodologies help towards an understanding of the underlying physical metallurgy of fatigue behaviour.

The failure of hardmetals and hard PM materials can be dictated by occasional defects, and therefore a large scatter is typically found in both strength and fatigue testing. Previous work at NPL on hardmetals has shown that flexural strength is determined by one of two factors; the distribution of large defects (pores, large WC clusters, etc) with a size greater than approximately 20 µm and the intrinsic strength of the average microstructure [4]. In order to minimise the risk of failure in testing from such defects, and to promote failure from 'normal' microstructure, at NPL we have investigated a simple test geometry through the use of V-notched test pieces to obtain S-N data in $R > 0$ flexural tests.

Test-piece preparation

For this test, rectangular test-pieces are ground on all sides to produce 40 × 5 × 2 mm bend specimens. Test-pieces are then V-notched on one of the 40 x 2 mm faces to a nominal depth of 1 mm using a profiled resin-bonded diamond wheel, removing material at about 0.002 mm per pass. The radius of the root of the finished notch is 0.5 mm and the included angle between the faces of the notch is 90°. For hardmetals, the notched test-pieces are annealed at 800 °C for 1 h in a vacuum to relax residual stresses due to machining.

Using Neuber notch theory [5], this geometry has a stress concentration factor at the notch root of approximately 4, compared with the nominal flexural stress of an unnotched test-piece of the same size.

Test jig

We have used a straightforward, commonly available four-point flexural testing jig with 10 mm inner span and 30 mm outer span [6, 7] to produce a uniform bending moment over the region of the notch.

Room temperature test results

Figure 1 shows results at room temperature for a range of hardmetals listed in Table 1. The indicated force is the peak force in the $R = 0.1$ cycle. Clear trends of increasing fatigue life with reducing flexural force is indicated, with relatively low scatter. Differences between different grades of material can be clearly discerned.

Table 1: *Hardmetal codes*

Code	Hardness HV30	Nominal WC grain size, µm	Nominal cobalt content, wt%
ma6	1518	1.03	6
ma11	955	5.16	11
t25	980	0.77	25
d10	1336	1.05	10
cw3	1918	0.4	3
ma14	1165	0.91	14
×160	1626	0.64	10
k3520	883	2.30	20

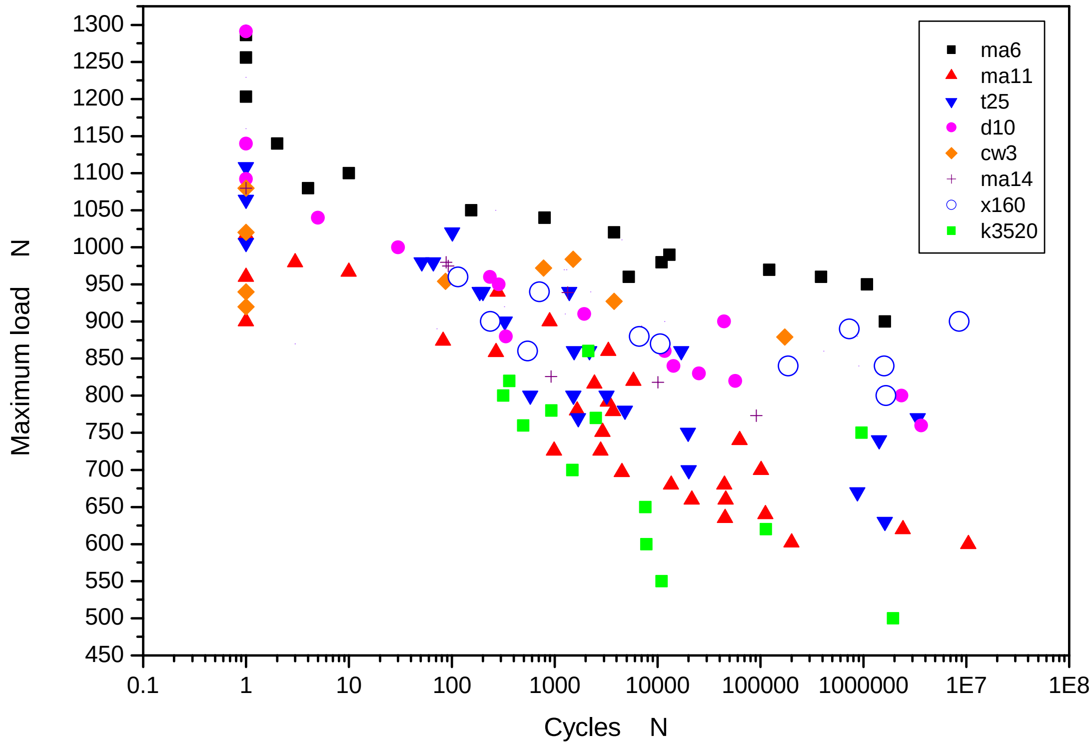


Figure 1: *Fatigue(R = 0.1) of notched test-pieces of various hardmetals at room temperature. Data points at 1 cycle represent short-term flexural strength. There is clear fatigue behaviour out to at least 10^7 cycles. A peak cyclic force of 1000 N corresponds with a stress in the notch root of about 2.46 GPa.*

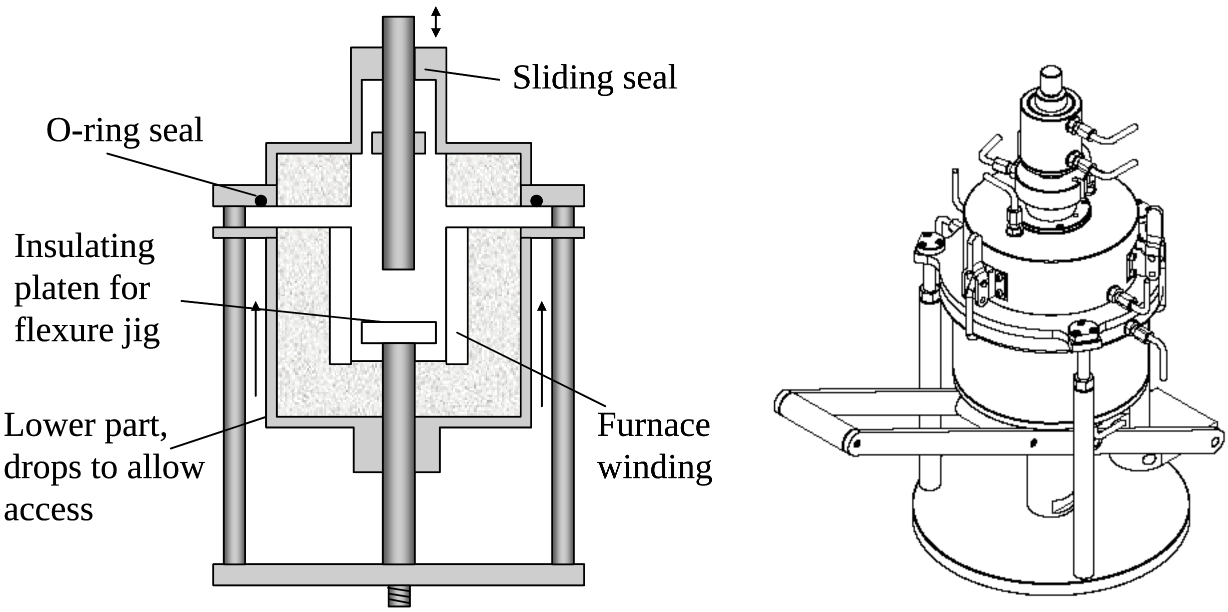


Figure 2: *(left) schematic of furnace structure, and (right) view of the unit.*

High-temperature testing

In order to perform high-temperature tests, the principal considerations are that a protective atmosphere is needed to minimise oxidation effects, and that for low-force testing (<1 kN), as needed by small notched test-pieces, requires minimal parasitic losses of force transmission in the loading system. To achieve this, a unit (Figure 2) was specially designed to mate into a standard Instron 8872 20 kN fatigue machine frame. Parasitic losses were minimised by minimising the load train mass and relying on the push rod having a loose sliding fit through the top of the unit. The lower half of the Kanthal A1 wire wound furnace can be lowered to gain access to the flexural test jig placed on an alumina ceramic thermal insulating plate located on the lower pillar. The case was internally water cooled, as was the seal region and the connector to the machine ram. The unit was designed to operate under continuous inert gas purge (nitrogen or argon) which leaked from the system through the freely sliding loading shaft, and through heater element and thermocouple lead-throughs. Once purged, the unit was capable of minimising oxidation on the test-pieces, and only a slight discoloration resulted.. The temperature of the furnace was controlled by a Type R thermocouple close to the heating element to ensure stable control at relatively low temperatures, and the test-piece temperature was monitored by a second Type K thermocouple passing into the chamber through the upper part of the furnace case, with its tip lodged inside the flexure jig.

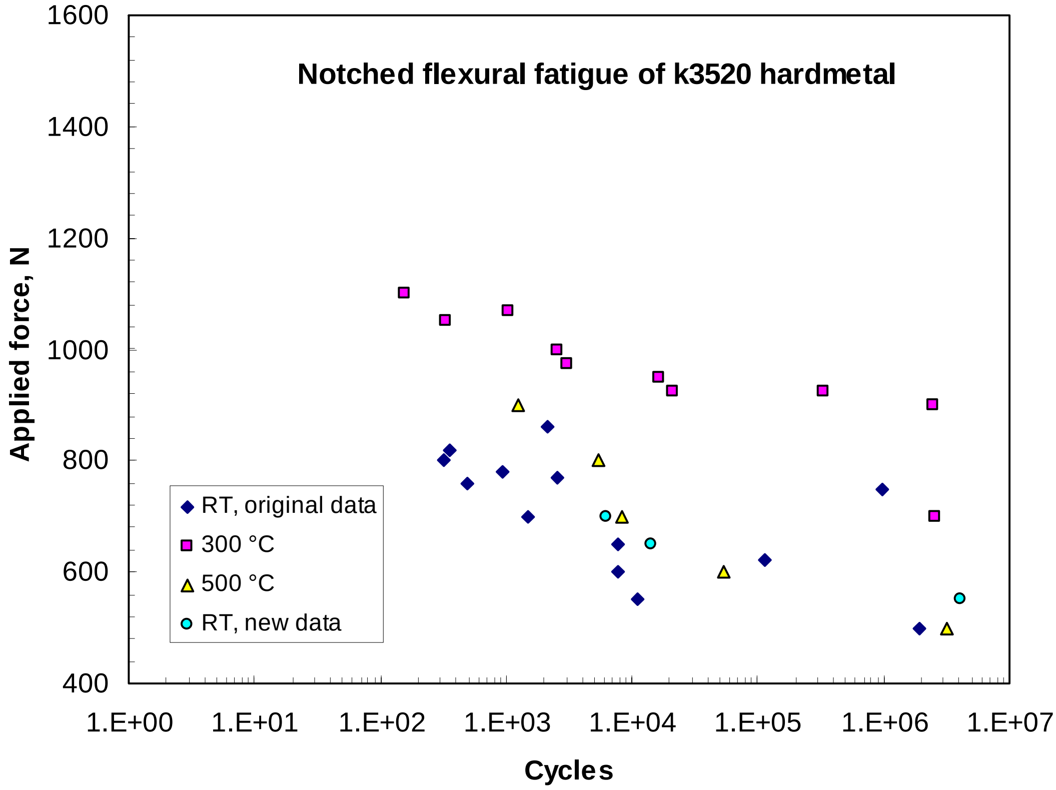
Initial trials showed that a power level of a few hundred watts only was required to achieve a test-piece temperature of 500 °C, which stabilised about 30 minutes after the somewhat greater peak control temperature was reached.

Hot fatigue test results

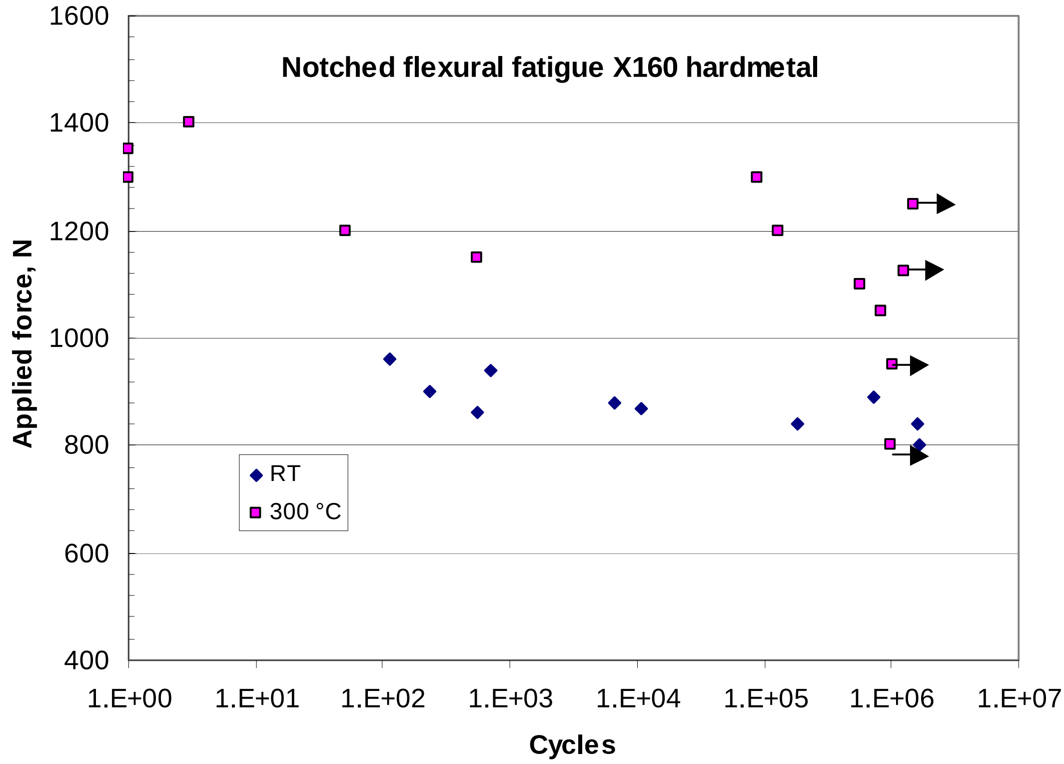
Figure 3 shows some examples of hot flexural fatigue test results on two of the materials shown in Figure 1, ×160, which has a fairly shallow curve, and k3520, which has a steeper fatigue curve a room temperature. It is immediately clear that in both cases, the fatigue strength at 300 °C is greater than at room temperature, while in the case of k3520, at 500 °C it is similar to that at room temperature. There was minimal oxidation of test-pieces, any effects noted being mainly a result of insufficient inert gas flow in initial tests. Fractography of fractured test-pieces (Figure 4) demonstrates near-surface microstructural failures at all test temperatures, but no obvious fatigue crack arrest features. Further work needs to be undertaken at high resolution to seek explanations for the changes in fatigue behaviour, which may be associated with tessellated residual stresses between the carbide phase and the binder phase and its relationship to microcrack initiation.

Conclusions

A hot flexural fatigue unit has been designed and built for the purposes of testing powder metallurgical and hardmetal materials at raised temperature. The unit has operated well for hundreds of hours and has enabled the production of fatigue curves for two hardmetals with the interesting outcome for these materials that the fatigue strength at 300 °C is considerably greater than at room temperature or 500 °C. Further work needs to be undertaken to provide an explanation of this behaviour, and to establish whether it is replicated in a wider range of materials.

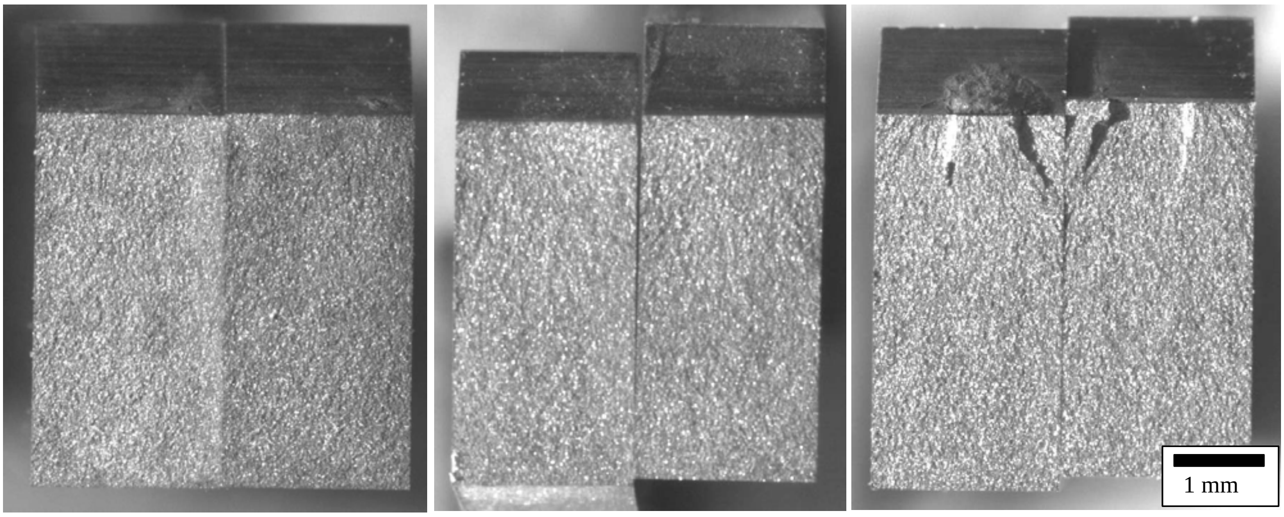


(a)



(b)

Figure 3: *Hot notched flexural fatigue tests (R=0.1) compared with room temperature tests for (a) k3520 and (b) ×160 hardmetals. A peak cyclic force of 1000 N corresponds with a stress at the notch root of about 2.46 GPa.*



(a) *(b)* *(c)*

Figure 4: *Fracture faces of fatigue test-pieces of k3520 hardmetal (a) RT, peak stress 1.72 GPa, 6351 cycles to failure, (b) 300 °C, peak stress 2.40 GPa, 3033 cycles to failure, (c) 500 °C, peak stress 1.72 GPa, 8467 cycles to failure (note spall on one side of notch surface as well as much rougher initiation zone).*

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