FATIGUE IN SOME ALUMINIUM ALLOYS WITH CONSTANT FORCE OR CONSTANT AMPLITUDE CONTROL AT 20 kHz.

by

B. S. Hockenhull
C. N. Owston
R. G. Hacking
SUMMARY

An improved 20kHz fatigue apparatus has been constructed. This equipment allows tests at up to 50% higher strain levels than those achieved with earlier apparatus and also has the facility of control of amplitude, force or power during test. Preliminary evolution tests have been made on the equipment and these are described.
INTRODUCTION

The possibility of fatigue testing at high frequencies has been considered for some time now and a number of experiments have in general established a frequency effect at least in some materials. The potentiality of such a high frequency test for accelerated fatigue evaluation is worth exploring if correlations could be established between high and low frequency test results.

Recent work (Refs. 1, 2, 3, 4) has described experiments in fatigue testing aluminium alloys at 20 kHz and has compared microstructural changes taking place at high and low frequencies.

The method so far developed consists of a mechanically resonant system excited by a magnetostrictive transducer. A train of acoustic transformers gives amplitude magnification and is designed to produce a sinusoidal strain distribution in a plain cylindrical specimen which is one half wavelength long. A piezo-electric crystal is glued to the free end of the transducer and this provides a voltage output proportional to the acceleration of the transducer end. For convenience this is referred to as the force signal although there is no simple relation between this "force" and the desired amplitude of the specimen. The voltage gives a feedback signal for the amplifier driving the system. The vibration amplitude of the end of the specimen is monitored optically and from this the peak stress level in the specimen is given by:

\[ q_{\text{max}} = \frac{\pi Ed}{2L} \]

where \( d \) is the measured displacement amplitude range, \( L \) is the specimen length and \( E \) is the dynamic modulus of the specimen material.

In theory it should be possible to design the components of the mechanical system so that the acoustic reflections either within the components or from the junctions between them are minimized for example by combining the transformers as a single component to reduce the number of junctions. In practice it is difficult to achieve these conditions and in any case it is possible that fatigue damage in the specimen may invalidate the matching. It is therefore more appropriate to regard the magnetostrictive transducer as a source of acoustic waves which are reflected back from discontinuities in the mechanical system and from the open end of the specimen. Previous equipment of this type (Refs. 2, 3) provided an approximately constant force mode of operation and experience showed that the specimen amplitude varied during fatigue tests. The resonant frequency of the system also showed changes up to 0.5 kHz part of which may have been due to the poor phase versus frequency characteristics of the electronics. It was desirable therefore to construct an electrical system which would eliminate these difficulties and provide alternative modes of operation. This note describes the construction of this equipment and its application in some fatigue tests at 20 kHz.

THE APPARATUS

No changes were made to the mechanical system. Three distinct modes of operation are possible.

(a) Constant power. The electrical input to the magnetostrictive transducer is
maintained constant and the amplitude of the mechanical oscillations builds up until the energy loss is equal to that supplied electrically. This mode of operation corresponds to the practical case of vibrations set up in a component which is weakly coupled to the source of vibration. The amplitude in the component is determined by the mechanical properties of the component rather than by the source of vibration.

(b) Constant amplitude. A feedback loop in the electrical system controls the power supplied to the transducer so that the amplitude of vibration at the specimen, monitored electrically, is maintained constant. The practical equivalent is that of a component strongly coupled to a powerful source of vibration so that the amplitude at the component is not influenced by changes within the component.

(c) Constant force. In this mode, the amplitude produced by the magnetostrictive transducer is maintained constant. The acoustic wave transmitted towards the specimen has a constant amplitude but the energy entering the specimen and hence its amplitude of vibration will depend on the acoustic properties of the specimen. If these change during a test, so will the amplitude of vibration of the specimen. In practice this mode represents an intermediate stage between (a) and (b), that is a medium degree of coupling between the source of vibration and the component.

A block diagram of the apparatus is shown in Fig. 1 and the parts will be described in the sections below.

THE AMPLITUDE MONITOR

When the apparatus is operating, the end of the specimen oscillates longitudinally at the working frequency (20 kHz) and may also move slowly longitudinally and laterally due to thermal expansion. The amplitude monitor must record the high frequency oscillations and be insensitive to the slow movements.

The simplest possible amplitude sensor is the parallel plate capacitor arrangement shown in Fig. 2(a). Movement of the specimen modulates the capacitance between the specimen and the fixed plate, a charge/discharge current flows through the series resistor R and produces a potential difference which is related to the movement of the specimen. Neglecting edge effects the capacitance \( C \) between the specimen of end area \( A \) and the fixed plate distance \( d \) from the end of the specimen is

\[
C = \frac{\varepsilon_0 A}{d}
\]

where \( \varepsilon_0 \) is the permittivity.

If the specimen is vibrating with amplitude \( d \), at an angular frequency \( \omega \) then

\[
d = d_o + d_1 \sin \omega t
\]

where \( d_o \) is the mean value of \( d \).
Therefore

\[ C = \frac{\varepsilon_o A}{(d_o + d_i \sin(\omega t))} = \frac{\varepsilon_o A}{d_o} \left(1 - \frac{d_i}{d_o} \sin \omega t\right) \]

The output voltage across \( R \)

\[ V_R = \frac{\varepsilon \delta C}{\delta t} \frac{A R V \omega}{d_o^2} d_i \cos \omega t \]

where \( V \) = supply voltage connected to the fixed plate via resistor \( R \).

To obtain a reasonable signal to noise ratio from the sensor, \( d_i \) had to be less than 0.3 cm. Thermal expansion of the acoustic transformers and specimen owing to heating during a test could produce a change of over 0.03 cm. in \( d \) and hence a change of more than 20% in the output voltage of the sensor. Further, the calibration of the sensor depends markedly on the value of \( d \) making resetting after specimen changes very difficult. The major advantage of the system was its freedom from sensitivity to lateral movement of the specimen. The mean distance of separation could be kept constant using a servo feedback system on the capacitative transducer. Such a technique has been tried on a high frequency fatigue testing machine (Ref. 5) but it is an expensive and complex system.

A successful sensor which was adopted was the coaxial system (Fig. 2(a)), the specimen (radius \( a \)) forming the inner conductor of a cylindrical coaxial capacitor (bore of outer cylinder \( b \)). The capacitance \( C \) between the specimen and the outer cylinder, neglecting end effects, is

\[ C = 2\pi \varepsilon_o / (\log_e (b/a)) \]

If \( d_i \) = penetration of the specimen into the outer cylinder and, as before, \( d = d_o + d_i \sin \omega t \), then the output voltage across \( R \), \( V_R \), is given by

\[ V_R = -2\pi \varepsilon RVd_i \cos \omega t / (\log_e (b/a)) \]

The output voltage is therefore independent of the mean insertion \( d \) so long as it is great enough to avoid end effects in the cylindrical capacitor. Practical tests on a device with \( b = \frac{1}{32} \) and \( a = \frac{5}{32} \) confirmed this freedom from sensitivity to slow longitudinal movements and also showed that the calibration was unaffected by lateral movements of up to 50% of the clearance between specimen and cylinder.

The electronics associated with the amplitude sensor is shown in Fig. 2(b). The output from resistor \( R \) (two 4.7 M\( \Omega \) resistors in series) is d.c. coupled into a simple pre-amplifier which has a high input impedance provided by an insulated gate field effect transistor. The output from the pre-amplifier is fed via a screened cable to the main amplifier which is located close to the rest of the electronic equipment. This main amplifier has a pre-set variable gain which is adjusted so that maximum specimen amplitude gives an a.c. output of 0.35 V. r.m.s. and full scale deflection on the meter. The meter can be calibrated to read the amplitude of vibration of the end of the specimen but requires recalibration if the specimen diameter
is changed.

INPUT SELECTOR

There are three variables in the apparatus, power, force and amplitude, any one of which may be required to be held constant during a fatigue test. In general the two variables not held constant will vary independently during fatigue test and changes in either of them can be used as in indication of structural changes or fatigue damage in the specimen. In order to terminate a test when a predetermined change has taken place in the specimen, either of these two variables can be fed to a memory and gating unit which switches off the apparatus when the chosen variable has changed by some preset factor.

The input selector unit (Fig. 3) contains appropriate buffer amplifiers and attenuator networks so that each input signal produces a standard level of 0.35 V r.m.s. when the apparatus is operating at maximum. These standardised signals are available at monitor points for measurements, examination by C.R.O. or recording on a chart recorder if full records are required for any test.

The seven way switch in the input selector unit selects the mode of operation of the apparatus. The available modes are:

<table>
<thead>
<tr>
<th>Switch position</th>
<th>Mode Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>external oscillator, constant power, no gating</td>
</tr>
<tr>
<td>2</td>
<td>constant power, gate on force</td>
</tr>
<tr>
<td>3</td>
<td>constant power, gate on amplitude</td>
</tr>
<tr>
<td>4</td>
<td>constant force, gate on power</td>
</tr>
<tr>
<td>5</td>
<td>constant force, gate on amplitude</td>
</tr>
<tr>
<td>6</td>
<td>constant amplitude, gate on power</td>
</tr>
<tr>
<td>7</td>
<td>constant amplitude, gate on force</td>
</tr>
</tbody>
</table>

LEVEL CONTROL

With the exception of the external oscillator mode, the apparatus is self oscillating at the resonant frequency of the mechanical system. Signals from either the force crystal or the amplitude monitor are fed via the input selector to the gain controlled amplifier, thence through an electronic gate to the power amplifier and back to the mechanical system with such a phase as to sustain the oscillations, (Fig. 1). The loop gain is +1 when the gain of the gain controlled amplifier is about 0db. The variable gain component in the gain controlled amplifier is a National Semiconductor integrated circuit type LM370. The integrated circuit gives the appropriate gain when about 2.4 volts d.c. is applied to the gain control connection.

The signal which is to be kept constant (power, force or amplitude) is fed to the a.g.c. amplifier and detector (MC 1709 and associated circuitry, Fig. 4). The gain of this amplifier, controlled by the 'SET LEVEL' control, is adjusted until an a.g.c. voltage of 2.4 volts is produced from the input signal. This a.g.c. voltage is applied to the LM370 to control the oscillator loop gain. As the gain of the LM370 varies by about 20 db per 100 mV change in a.g.c. voltage, a change of some 4% in a.g.c. voltage or signal input will vary the power to the magnetostrictive transducer by a factor 10. This is adequate gain in the level control loop to ensure good stability of the desired...
constant signal.

MEMORY UNIT AND GATING

Whichever signal is to be used for gating, i.e., to terminate a test run when a predetermined amount of damage has been produced in the specimen, is fed to a memory unit (Fig. 5). With the whole apparatus running, the gain of the first amplifier (MC1709C) in the memory unit is adjusted by the 'SET MEMORY LEVEL' control unit until a d.c. output of 6 volts appears across the 1.0 μF reservoir capacitor C. This output voltage is just sufficient to give a voltage across diode MR 1 equal to that across MR 2 and so give zero output voltage from the first LH201 integrated circuit. This balanced condition is indicated by zero deflection on the centre zero meter M. When the amplitude of the input signal to the memory unit changes from its initial value the voltage across C and across MR 1 both change and a d.c. output voltage appears from the first LH201.

In some modes of operation of the high frequency fatigue apparatus the signal used for gating rises for a given change in the specimen while for other modes it falls. It was felt that the damage in the specimen corresponded more closely with the same factor change in signal rather than the same absolute change. If, when operating in the constant power mode, the specimen amplitude fell from 100 units to 50 units for a certain degree of damage then, in the constant amplitude mode, the input power would double for the same damage to the specimen. Because of the logarithmic relation between the current through diode MR 2 and the voltage developed across it, the input voltage to the first LH201 is proportional to the logarithm of the signal to the memory unit. If therefore an output of +6 volts appears from the first LH201 because of an increase of x2 in the input signal to the memory unit, an output of -6 volts is produced when the input signal falls to x0.5 of its initial value. The meter scale (M) is therefore calibrated x2, x1.5, x1, x0.67, x0.5.

The two diodes MR 3 and MR 4 on the input to the second LH 201 are normally both conducting as a result of the bias currents derived from the ganged 5 KΩ linear potentiometers. The input connections to the second LH 201 are such that when both sides are conducting the output voltage is hard positive. In this state MIR 5 conducts and only a small positive voltage appears at the gate signal output. If the input signal to the memory unit begins to rise above its initial value the output of the first LH 201 becomes positive and rises. Eventually this voltage will become high enough to reverse the voltage applied to MR 3 which then ceases to conduct, a positive voltage is applied to terminal 2 of the second LH 201 and the output voltage starts to fall. The positive feedback on the second LH 201 thereupon causes a rapid switch over, output voltage goes hard negative and a negative voltage appears as the gate signal.

This negative gate signal is applied to the base of the first transistor of the Darlington pair forming the output of the gain controlled amplifier system (Fig. 4) and so switches off the apparatus. The gate voltage is similarly applied to the square wave generator (Fig. 6) switching off this unit to stop the cycle counter. A manual/gated switch (Fig. 4) allows the automatic gating.
to be over-ridden and a stop/run switch allows a test to be stopped and restarted at any stage.

SQUARE WAVE GENERATOR, POWER AMPLIFIER

The square wave generator and the associated gate (Figures 1 and 6) is a simple buffer amplifier which provides a constant amplitude square wave suitable for driving the counter and frequency meter.

The power amplifier (Fig. 7) is a conventional valve power amplifier giving about 120 watts output. Because of the inductive nature of the load and the high voltages involved a valve amplifier was preferred to a solid state one. Capacitors are connected across the output terminals to provide power factor correction. The power amplifier and the d.c. supply to polarise the magnetostrictive transducer are housed in a separate unit from the remaining electronics. This provides good shielding between the input and output of the electronics with consequent good stability and freedom from parasitic oscillations and also protects the solid state electronics from the high voltages in the valve amplifier.

OPERATING THE APPARATUS

Operation is extremely simple. The manual/gated switch and the stop/run switch (Fig. 4) are set to manual and stop respectively, the equipment switched on and allowed two or three minutes to warm up. The specimen is attached to the acoustic transformers, the amplitude monitor placed in position, the counter set to zero and the "set level control" (Fig. 4) to minimum. The mode of operation is selected with the 7 way switch on the input selector. When the stop/run switch is set to the 'run' position the apparatus starts oscillating and the counter begins counting the cycles. The "set level control" is advanced until the desired level is achieved. If the apparatus is required to gate automatically the "gate width" (Fig. 5) is chosen and the "set memory level" control (Fig. 5) is adjusted until the meter M reads centre zero. The manual/gated switch is then moved to "gated". The apparatus will then stop oscillating at the completion of the test.

At any stage, a test can be interrupted by moving the stop/run switch to "stop". To restart one must first select "manual" then switch to "run" after which it is possible to return to the "gated" condition.

If successive tests are to be made under identical conditions it is not necessary to return the "set level control" to minimum.

For the present series of tests amplitude and force signals were monitored on digital voltmeters and could also be recorded. The amplitude was also monitored optically at the end of the specimen adjacent to the transformer in order to provide calibration information. Previous experiments (Ref. 2) and experiments using mode 4 indicated that the optical measurement of amplitude at both ends were within $\pm 3\%$ of each other.
RESULTS AND DISCUSSION

Although the apparatus has been designed primarily as a fatigue machine, it will also be used for dynamic property measurement, but at this stage it is only intended to report results gathered during evaluation of the apparatus and the fatigue data so far obtained.

Tests have been made on two commercial aluminium alloys, Al-4.4Cu-0.7Si-0.6Mg-0.6Mn (L65) and Al-2.5Cu-1.5Mg-1Fe-1.2Ni-0.1Ti (RR58). The results confirm that the equipment is effective in producing higher strain levels than obtainable before and that the system is essentially stable.

The modes of operation which have been investigated so far are the constant force modes (Modes 4 and 5) and constant amplitude modes (modes 6 and 7). The first test was to attempt to relate the force signal to the optical and electrical amplitude, whilst the amplitude was changed incrementally. The information obtained is given in Fig. 8 which also shows the concurrent variation in the system frequency and the mean position of the end of the Fourier transformer.

Whilst at first sight there appears to be a good relationship between the amplitude and force signals, it should be made clear that this was a constant amplitude mode and the force signal in fact changes with time so that the correlation is not as good as at first sight. However the agreement between the "optical" and "electrical" amplitudes is good and suggests that calibration of the electrical amplitude device is feasible and linear although subject to variation with the manner of setting-up. There is also a reasonable correlation between the mean position of the end of the Fourier transformer and the frequency which suggests that the thermal expansion during test may be responsible for the frequency change. Explanation of the change in frequency is made more difficult by the fact that the dynamic properties in the specimen will change during fatigue and cause changes in the frequency in addition to those due to thermal changes in the system. However the change in frequency noted is only at most 100 Hz at the highest stress in this experiment and this change is rather smaller than those observed with the previous machine.

Further tests were made using modes 6 and 4, to study the variations in force etc. at constant amplitude and amplitude etc. at constant force. These results are summarized in Figs. 9 and 10. In each case the level of the force or amplitude was selected and increased after a reasonably steady state was reached in the other parameters. The constant parameter selected was indeed found to be constant to within 1%. It will be seen however that in the constant amplitude test there is some scatter, up to about 4%, in the optical amplitude readings. The force/amplitude relationships are shown clearly in that, following a step in constant force level there is an increase in amplitude which appears to go to a steady value. Similarly, in the constant amplitude case, an increase in amplitude level leads to an increase in the force signal which then tends to relax to a steady level. These effects are absent at low amplitude levels and so it is possible that they are associated with changes in the dynamic properties of the specimen material during cyclic stressing where there is a small plastic component. This could then be said to be due either to micro-structural changes, which would change the dynamic modulus, or simply to thermal softening of the material. In either case the process is one of fatigue softening in a strong alloy and this is consistent with results obtained...
previously (Ref. 4). Although temperature measurements have not been made the frequency changes tend to support this since there are unlikely to be accounted for simply by temperature changes although the calculation on which this is based is necessarily only rough for the somewhat complex system.

So far as fatigue tests are concerned there are three regions which give separate problems in high frequency testing. There are (a) High stress : short life tests, say up to $5 \times 10^5$ cycles, (b) Intermediate stresses with lives up to $10^7$ cycles and (c) Low stress : long life tests where lives may exceed $10^9$ cycles. In the first case, the life is short, up to say 25 seconds so that heating effects are less pronounced in that the temperature rise, although rapid is not large. However the major problem is achieving high strains in the specimens. The amplifier is now well matched electrically to the transducer but the transformer specimen train still presents some mismatch problems. These may be partially solved for instance by making the stepped and Fourier transformers of the same material and machining from a single solid piece of metal but this would make the transformer system, which has a finite life, rather more expensive.

A second problem at high strains is that it is not possible in a short time to read the amplitude optically and therefore it is necessary that the amplitude measurement device be pre-calibrated as accurately as possible. However the calibration is found to vary with the manner of setting up and great care must be taken. A simple split collet jig allows relatively simple and reproducible setting-up and this has been now adopted.

In the intermediate range the earlier machine tended to produce large scatter in the results because the stress level fell below its initial value and tended to take the stress into the long life region. Thus a specimen might start at $\pm 9$ tonsf in $\frac{1}{2}$ giving a predicted life in the region of $5 \times 10^7$ cycles but before it fractured, the stress level might fall to a level giving a life of $5 \times 10^5$ cycles. Preliminary tests indicate a reduction in the scatter among results in this region. In this region the heating problems are most severe since stressing at $\pm 15$ tonsf in $\frac{1}{2}$ causes fracture too quickly for the heating effects to be of much consequence and at low levels the temperature rise is not significant in relation to the fatigue properties.

In order to examine the sensitivity of the system to ambient temperatures and to the changes caused by resting the system and allowing it to cool, a series of tests were made on one specimen. These are summarized in Fig. 11. The 'force' level was maintained constant. The amplitude level varied with ambient temperature and, after the specimen had been rested for periods such as 5 minutes, with time. This suggests that thermal changes are responsible.

In the long term tests the chosen constant parameter has been shown to remain constant up to $10^7$ cycles.

With this apparatus, an extension of fatigue data at 20 kHz to higher stress levels is possible and the confidence in the results at lower levels is improved. All results still demonstrate that the frequency effect is present, although this has not been found by other workers (Ref. 5) in similar alloys. In their case however, it is considered that too few results were obtained and the complex geometry of the specimens may have had a masking effect.
The high stress results obtained suggest that the frequency effect is reduced at higher stress levels and this again supports trends already found, (Ref. 2).
REFERENCES


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5. BRONDEAU, M. Machines d'essais de fatigue à fréquence ultrasonores. Arts et Metiers, October, 1969.
FIG. 1. BLOCK DIAGRAM OF HIGH FREQUENCY FATIGUE APPARATUS
FIG 2(a) HIGH FREQUENCY FATIGUE APPARATUS - METHODS OF AMPLITUDE TESTING

FIG 2(b) HIGH FREQUENCY FATIGUE APPARATUS - AMPLITUDE MEASURING DEVICE
FIG. 4. HIGH FREQUENCY FATIGUE APPARATUS - A.G.C. SYSTEM AND GATE
FIG. 5. HIGH FREQUENCY FATIGUE APPARATUS – MEMORY UNIT

FIG. 6. HIGH FREQUENCY FATIGUE APPARATUS – SQUARE WAVE GENERATOR & GATE
FIG. 7. HIGH FREQUENCY FATIGUE APPARATUS - POWER AMPLIFIER
FIG. 8.

FIG. 9. OPERATION IN CONSTANT AMPLITUDE MODE
MATERIAL L65
MODE 4 (CONSTANT FORCE)
INITIAL FREQUENCY 19.616 kHz.

FIG 10 OPERATION IN CONSTANT FORCE MODE

FIG 11. TRANSIENT READINGS