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Crack Propagation in Light Alloys

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- by -

A. Younger

SUMMARY

The revised approach to the measurement of the rate of crack propagation in light alloys has entailed the development of new experimental techniques, in particular the development of a multi-channel interval timer. The design of this instrument and descriptions of the new techniques are reported here together with the results of some preliminary evaluation tests.

Introduction

The reconciliation of the two current approaches to the study of fracture phenomena is a task of considerable theoretical importance and practical consequence. The continium approach, reviewed by Drucker[1], assumes a simple model of a homogeneous work-hardening solid with small sharp incipient cracks. Although this model ignores many facets of the structural changes occurring in metals during straining its predictions accord with many experimental results. It is reasonable therefore to conclude that these macroscopic theories have, at least, partial validity.

The atomic, microstructural approach, as reviewed by Low[2] concentrates on specific atomic mechanisms involved in the separation of crystal planes, with regard both to nucleation and propagation of failure. It has been shown metallographically[3] that ductile fracture in some aluminium alloys occurs by a void growth mechanism. The precise path of fracture depends on the plastic behaviour of the aluminium matrix and upon any features which may localize the strain. Two such features are the shape and distribution of precipitate particles and the existence of depleted boundary zones adjacent to grain boundaries. The narrow depleted zones provide an easy fracture path, nucleation occurring by fracture around grain boundary precipitates. These grain boundaries in age-hardening alloys may contain over-aged precipitate particles and fracture can occur by the linking of cracks generated around these particles. Both these mechanisms give intercrystalline fracture. The transcrystalline fractures observed in some alloys has been attributed to nucleation by precipitates located in the slip bands.

When considering propagation, certain questions at once arise:

1. For a given stress level, what proportion of these precipitate particles, whether located in the grain boundary or within the grain, act as nuclei for cracks? Are there any differences between coherent and non-coherent particles?

2. What is the average path length between these active nuclei?

This mean path length is the distance each of the precipitate cracks must travel before a void sheet separation occurs. In this connection the shape of the precipitate may be of considerable importance. A single crack propagating from a rounded particle located at random in a crystal must travel until it reaches a second particle or cuts a second crack. Alternatively a flat particle located in a slip band may propagate cracks from both ends of the particle, and these cracks will not be randomly angled from the particles but will propagate along the slip bands. If there are a large number of such particles in the slip band the mean free distance for the crack to propagate will only be half the inter-precipitate spacing along the slip band.

3. Once a crack is formed and has grown to a limited extent, does further propagation depend on a continuance of the initial mechanisms or does the initial crack provide a sufficient stress concentration for cleavage to occur? The first possibility would suggest a smooth, slightly accelerating (due to the stress concentration factor) growth rate: the second would suggest catastrophic failure at a critical path length. In the slip band precipitate mechanism it would be of interest to know the effect of precipitate thickness on the stress-concentration and consequent growth rate.

4. Can certain types of precipitate act as crack arrestors?

The answers to these questions demand two experimental requirements.

a) a precise knowledge of the microstructure of the material under investigation.

b) a precise knowledge of the rate of propagation.

It is with these precepts in mind that the present investigation has been undertaken. A range of common aluminium alloys, on which there is a considerable mass of published structural work, has been acquired. On these alloys precise measurements of the propagation rates will be undertaken with regard to the following variables:

a) state of heat-treatment of the alloy,
b) strain rate,
c) temperature.

The measurement of crack velocities at realistic strain rates has entailed the design and construction of some sophisticated measuring equipment and techniques. The development of this equipment, the techniques involved, and the discarded possibilities are discussed in this report.

2. Experimental Work

The basis of the experimental work was the work reported earlier[4] which showed some promise. In this work two fine wires were rigidly adhered to a metal surface. As a crack passes under the wire, separation at the surface occurs and the wire fractures. By timing the interval between the fracture of a pair of wires, the rate of propagation may be measured. The two-wire technique however only measures an average rate of crack growth and provides no evidence of any acceleration that may occur. The technique has therefore been extended to a multi-wire system by the attachment of a grid of 11 wires uniformly spaced. This grid enables the rates to be determined for 10 linear intervals. The timing apparatus has been developed to cope with a wide range of time intervals (10^{-7} - 10 secs) and to provide data irrespective of the initial point of cracking and the growth direction.

The two main lines of work will now be described:-

2.1 Grid Assembly

The following possible types of measurement that might be used for measuring crack speed were considered:

1. Measurement of the change in electrical resistance of a specimen as a crack passed across it, so reducing its effective cross-section. Initial experiments showed that in the early, interesting stages of fracture the change in resistance was an extremely small quantity in an overall large reading, thus giving poor accuracy. The use of a high frequency current may have improved the situation but would necessitate a considerable amount of equipment. With these methods recording would not be easy due to the range of signal to be expected.

2. Direct transmission of light through the specimen onto a moving film. This would be a simple, self-recording technique but demands that the crack is perpendicular to the surface, and that a sufficient intensity of light will pass through a fine crack.

3. A grid of wires rigidly attached to the surface. Three possibilities were investigated:

a) A grid formed by electroplating, or vapour deposition, onto the metal surface. These methods are technically feasible and would give a reproducible grid. They require considerable plating or vacuum equipment if a large specimen size is to be used. The grid when prepared would mechanically have to match the substrate properties.

The grids would also be very delicate to handle.

b) A vapour deposited and electrodeposited coat on the specimen could be precision etched to give a grid. With this process it would be easier to match grid and substrate properties, mainly ductility, but the etching process would be expensive (about £12 per specimen) if carried out commercially.

c) The use of fine wires adhered to the surface as used in the two-wire technique. This technique has certain advantages:

i) It is cheap.

ii) The ductility of the wires can be adjusted to match the ductility of the specimen.

iii) The properties of the adhesive can be varied to give good compliance for a range of ductilities.

iv) The completed specimens are fairly robust.

The major disadvantages initially were that it was a very time consuming process fastening the wires and the reproducibility of the wire spacing could not be guaranteed. In view of the advantages of this method a special jig was built to overcome these disadvantages.

2.1.1 Winding Jig

This jig is shown in the photograph in Fig. 1.

A perspex carrier has two specimens, one on its front face and one on its rear. The carrier can rotate about its centre to bring either specimen upper-most. The specimens are located by pins on the carrier, fitting into jig drilled holes on the specimen. A piece of Vero-board strip is stuck on to the surface (see Fig. 2) of the specimen.

Fine wire from a tensioned spool is attached to the specimen, which is coated by an adhesive (see below). As the specimen is rotated the wire is pulled down into the adhesive so fixing it. The wire is located by passing through fine slits mounted on the two ends of the specimen carrier. A PTFE strip clamps onto the specimen holding the wires in position until the adhesive has set.

The wire used is cold drawn copper 0.001" in diameter. Ductility can be controlled by annealing.

The specimen arrangement is shown in Fig. 2. Since the electrical circuits do not demand that the crack starts and finishes at predetermined places and travels in a particular direction, there is no need to match the specimen. So long as failure occurs in the gauge length it will be recorded.

Adhesive

The first adhesive tried was of the 'Durofix' type. At fast strain rates the adhesive tended to peel rather than fracture at the substrate crack.

A resin based Araldite adhesive was then used. This adhesive does not normally have sufficient plasticity to cope with the elongation of the metal before fracture. Additions of Thiokol were therefore made to increase plasticity. The elongations achieved are shown in Table I.

Table I. Effect of Theokol additions on plasticity of adhesive

Vol.(ccs) of Thiokol 308	Vol.(cc) Araldite F	Elongation %
25	100	6
50	100	9
75	100	15
100	100	-
150	100	75

It has been found necessary to pre-clean the aluminium surface before applying the adhesive. The specimens are pickled in a potassium dichromate-sulphuric acid solution for about 30 minutes at 55°C. The surface is then washed, warm air dried and a thin base coat of the Araldite-Thiokol adhesive applied immediately. A second coat of adhesive is applied immediately before winding.

2.2 Multi-channel time interval measuring unit

This unit has been designed by the Instrumentation Department of this college and its construction is now almost complete.

A functional block diagram of the equipment is shown in Fig. 3.

A 50Ω miniature co-axial cable is used to connect the specimen wires to the apparatus 15 pole input socket. Each cable is terminated, for signal purposes by a 75Ω resistor in parallel with the 6V 40mA lamp. A bright glow of the lamp indicates that the wire is intact: this reduces to a glimmer when it is ruptured.

At the instant of rupturing, a positive-going step of 2 volts amplitude appears across the appropriate 75Ω resistor. Any one of these eleven 'wire signals' can be selected by any one of the ten interval timer units (Fig. 4) as either a start or a stop timing signal by means of the eleven way selector switches. At the same time the timebase unit required can be selected by the 5 way switch. The units available are 10^{-7}, 10^{-6}, 10^{-5}, 10^{-4} and 10^{-3} seconds. Each timer can have selected the same or any of these units independently. Each timer will have provision for up to four decades although only three are fitted initially.

A 5 mc/s crystal oscillator followed by a doubler stage is used to provide the basic 10 mc/s clock frequency for timing in 10^{-7} second intervals. This is followed by decade dividers using identical circuit boards to those used in the timer units (Fig. 5).

For economy purposes only one read-out display is provided. The timers are connected in turn via the 19 pole, 11 position switch to the lamp drivers. Again for economy the display is in a binary coded decimal form using a group of four lamps per decade. As the time available for read-out is not limited this procedure is not considered to be disadvantageous.

An additional feature is the provision of 'Direction' indicators, which indicates which of the two wires connected to each timer unit provided the start pulse. The control board of necessity has three bistables for the purpose as the system has five states

1 Reset (000)
2 Running started by an A pulse (100)
3 Running stopped by an B pulse (101)
4 Running started by an B pulse (010)
5 Running stopped by an A pulse (011)

In state 2 further A pulses are ignored.
In state 4 further B pulses are ignored.
In states 3 and 5 all further input pulses are ignored and state 1 can only be regained by the use of a reset button.

A further feature is that the timers are coherent. If therefore two timers, using different time bases are connected to the same pair of wires i.e. using 10^{-7} and 10^{-4} time bases a resolution of ±0.1 micro-second in ten seconds can be attained.

2.3 Preliminary Tests

In order to gain some insight into probable rates of propagation for the purpose of working out an experimental programme some preliminary propagation measurements have been made. The aluminium sheet alloy DTD687 was heat treated into 6 conditions (see Table II) and the fracture under tensile elongation filmed. The filming was carried out at 60 frames per second and the cine film printed out for measurement purposes. By measuring the length of the visible crack in successive frames the rate of propagation may be assessed. There is of course an upper limit to the usefulness of this method as at the faster crack speeds the complete failure occurs between successive frames. The fastest speed which could therefore be measured was 368 cms/sec.

3. Results of preliminary tests

The results are shown in table III

Table III

Condition	Slowest rate cms/sec.	Fastest rate cms/sec.	Average rate cms/sec.
1			min. 368 184
2			94 184 184 368
3	0.5 0.4 0.18 1.39 1.11	166.5 64.0 57.7	
4	0.21 0.45 0.32 0.29 0.65	 2.1 4.5	
5			min. 368 212 min. 368 167 min. 368
6			min. 368 min. 368 min. 368

It can be readily seen that ageing i.e. precipation induced to harden the lattice has resulted in a very considerable acceleration in the crack rate. Slow cooling however where massive precipitation would occur has had little effect on the propagation rate. The quenched alloy appears to show an accelerating rate rather more than the slow-cooled one. It must be stressed that these results were mainly intended to gather background information for further testing. They do however show the remarkable changes in propagation rates between aged and unaged materials, between solution treated and quenched, and the slow cooled condition. There appears, within limits of this experiment to be no difference between the fully aged and the overaged conditions. This may probably be due to the insensitivity of this test.

4. Programme of work

The time interval measuring unit is now almost completed, and will enable testing to be commenced shortly. Early tests may involve simultaneous testing using the measuring unit and a very fast (7000 frames/sec.) camera to check on the comparative results.

The alloys available for examination are listed in Table IV. Where appropriate these alloys will be tested in a whole sequence of heat-treatment conditions. Tensile tests have already been carried out on many of them for the purposes of matching wire and adhesive ductility with that of the specimens.

Acknowledgements

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References

1. Drucker, D.C. — Fracture of Solids. Conf. 1962. John Wiley for AIMME, 1963, pp. 3-50.

2. Low, J.R. — Prog. Mat. Sci. Vol. 12, pp. 1-96.

3. Ryder, D.A., and Small A.C. — Ref. 1, pp. 237-259.

4. Bennett, D. — Report on Contract.

Table II. Heat treatment of DTD687

Base Composition - Zn 5.7% Cu 1.3% Mg 2.9%

The material was supplied in the form of 16 SWG sheet. Five specimens were prepared in each condition.

Condition No.	Title	Solution Treatment	Ageing	Average Hardness VPN
1	As received	-		189
2	As received and overaged	-	5 days at 135	143
3	Solution treat and quench	2 hrs at 465°C		81.5
4	Solution treat and slow cool	"		63.4
5	Solution treat and aged	"	15 hrs at 100°C +2 hrs at 135°C	162
6	Solution treat and overaged	"	21 hrs at 100°C +18 hrs at 135°C	-

Table III. (See page 7).

Table IV. Alloys available for testing

Grade	Nominal Composition %					
	Cu	Mg	Zn	Mn	Si	Al
S1						99.99
S1C						99
NS3				1.2		rem.
NS4		2.25		0.4		rem.
HS15	4.6	0.7		0.75	0.8	rem.
HS30		0.9		0.7	1.0	rem.
NS6		5.0		0.25		rem.
NS7		7.0				rem.
755	1.3	2.5	6.0	0.3	0.8Cr	rem.
245	4.5	1.5		0.6		rem.

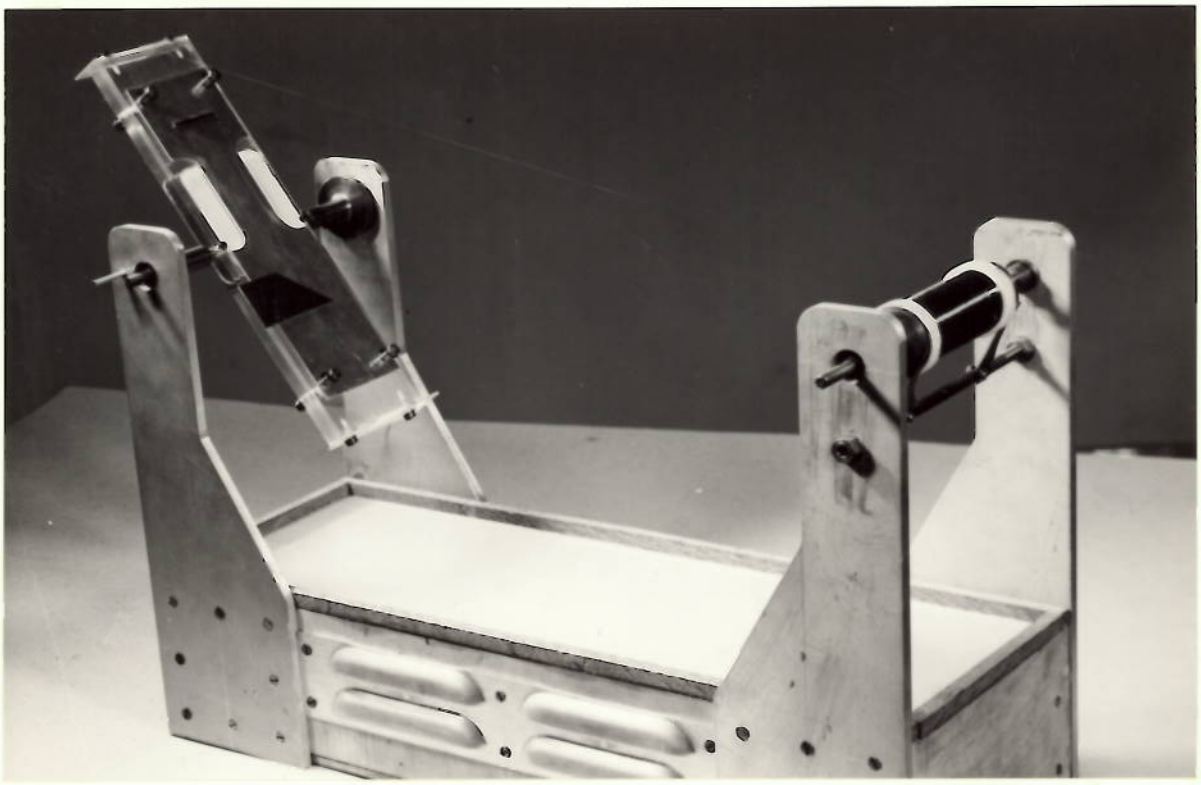


Fig. 1. Jig used for placing fine wires on the specimen

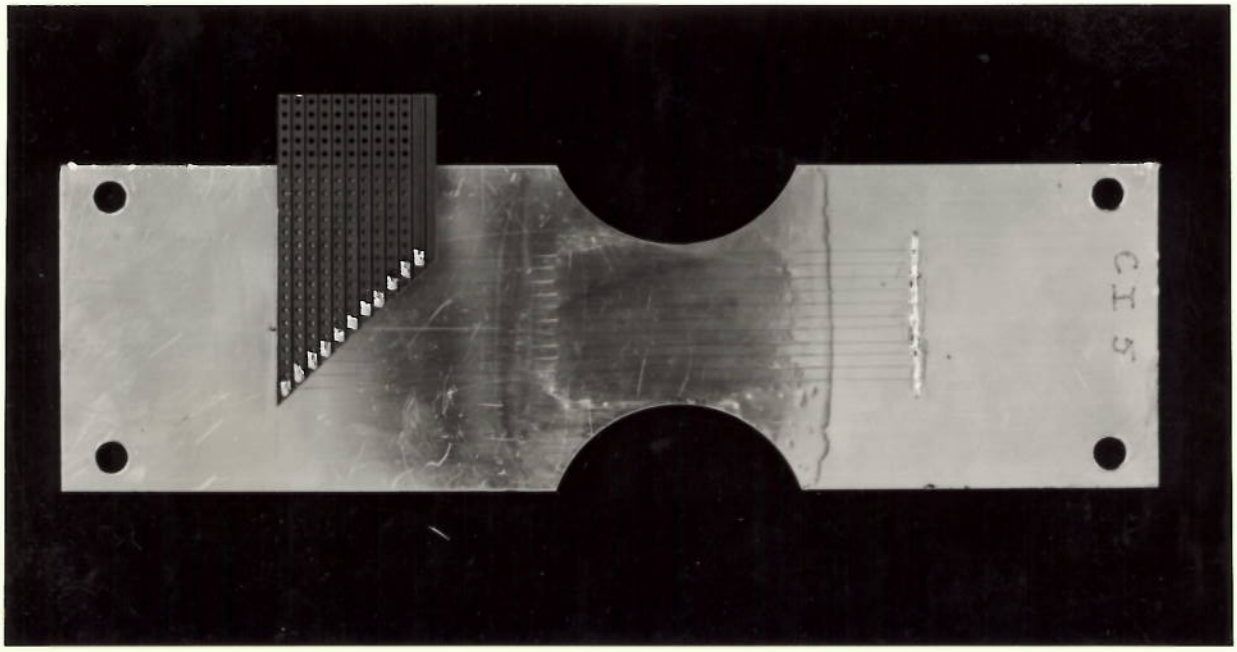
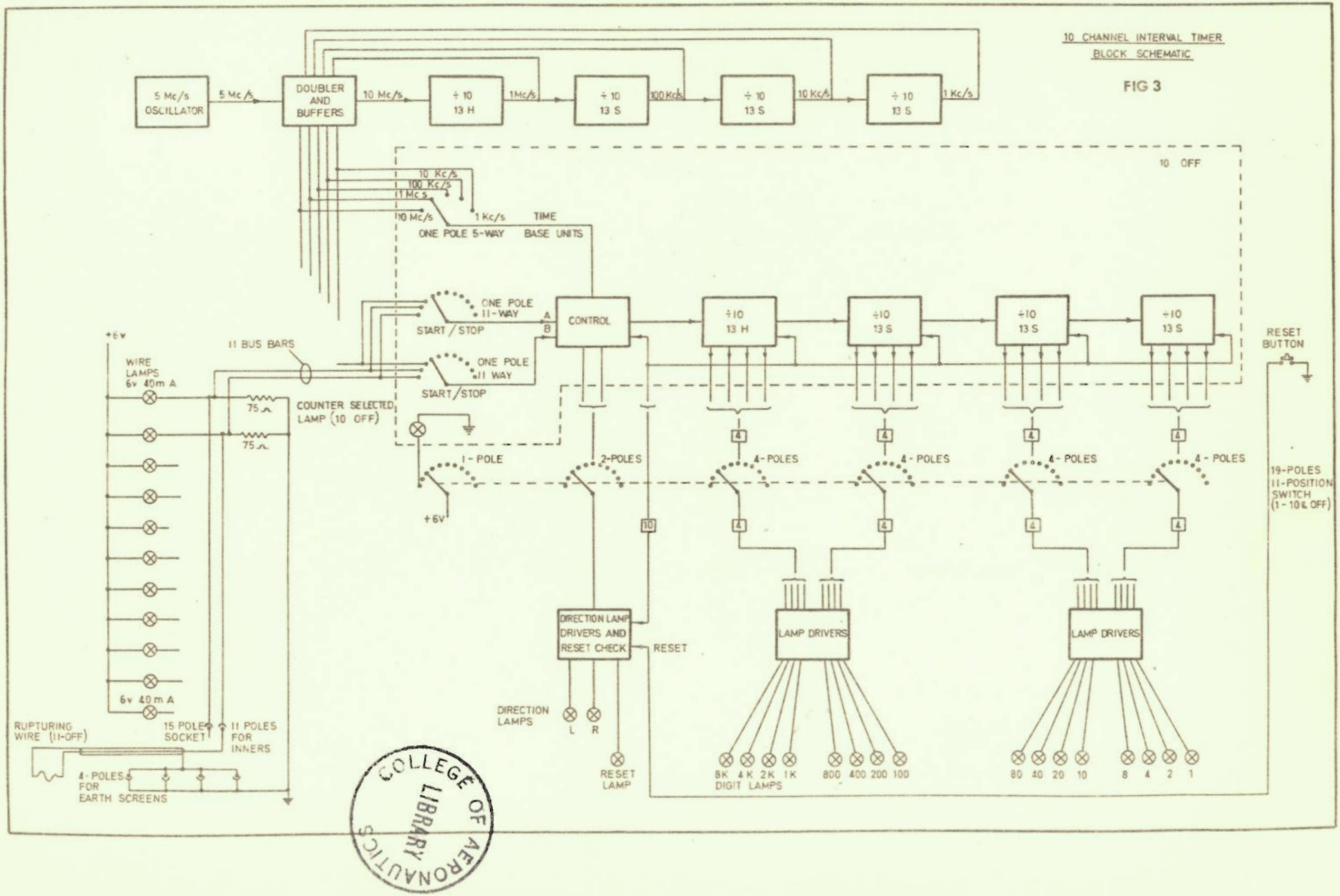
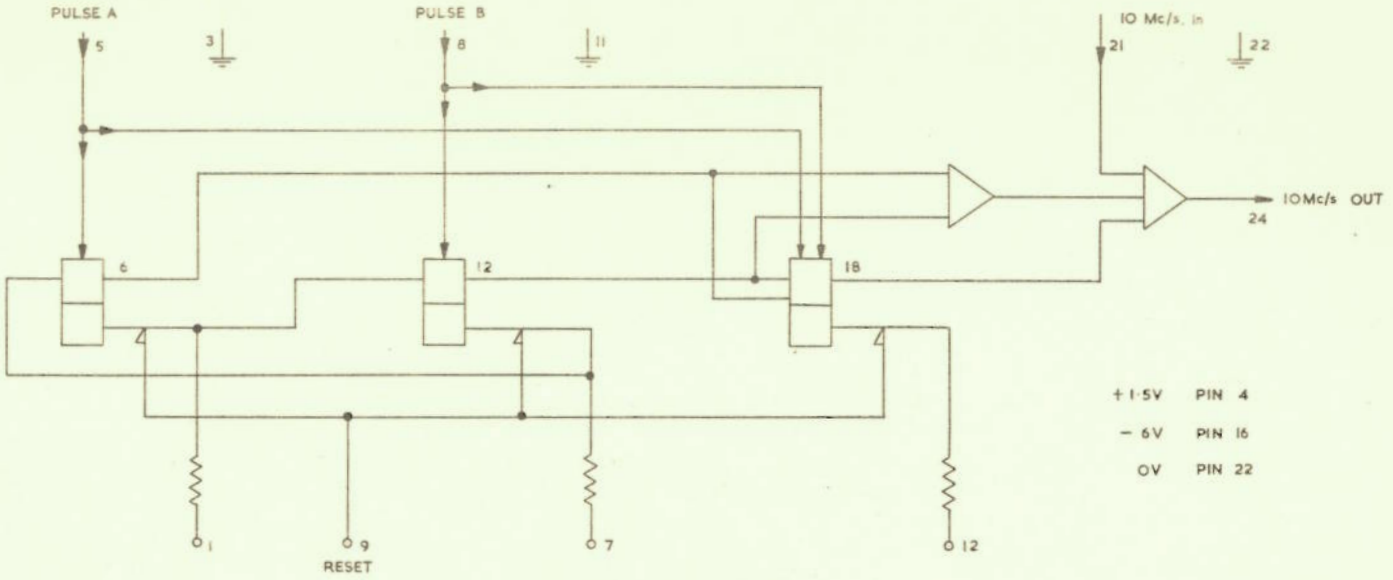
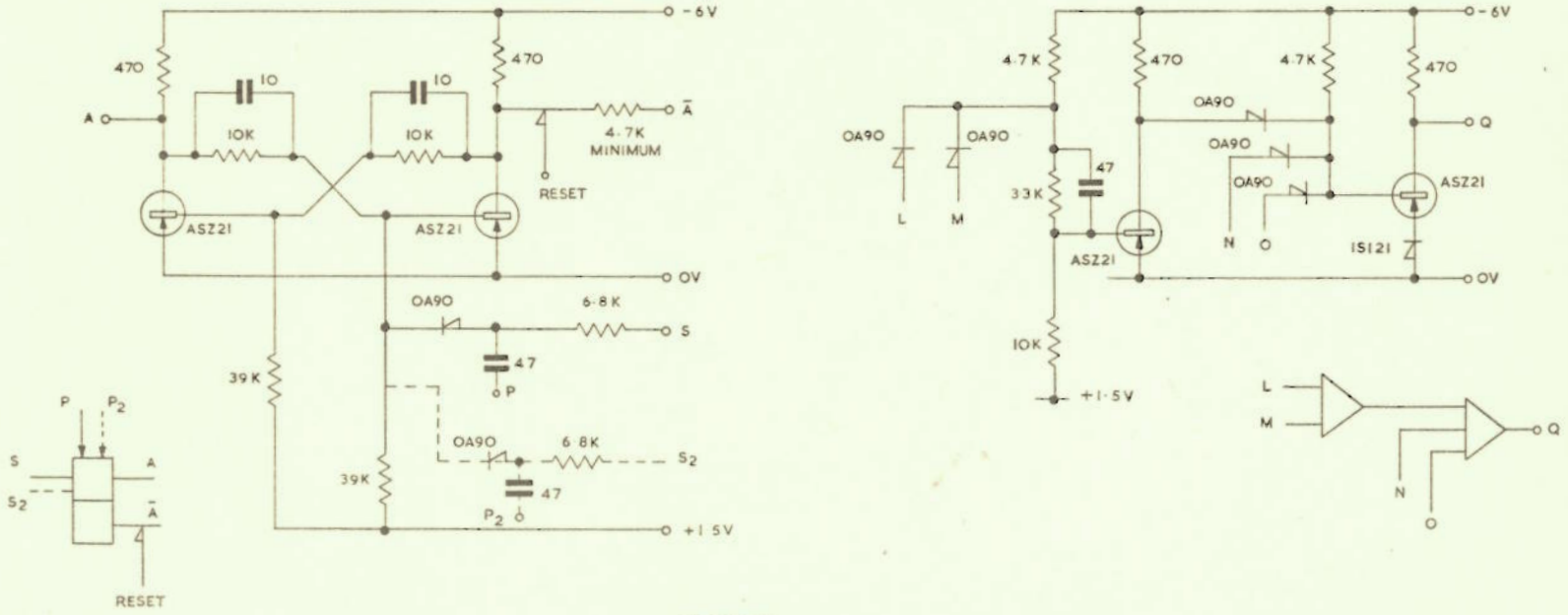


Fig. 2 Specimen





LOGICAL DIAGRAM



CIRCUITS

FIG. 4 DECIMICROSECOND STOP CLOCK DIRECTION INDICATING CONTROL BOARD

FIG. 5 **DECADE BOARD**