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1 INTRODUCTION

Perhaps the most serious problem encountered in the operation of superconducting magnets is that of the 'training' effect. This effect has been variously attributed to cracking of the encapsulant, frictional heating resulting from movement of the wire relative to the encapsulant, or general movement of the coil.[1] Notwithstanding these possibilities, some superconducting coils manufactured with careful attention to the above factors including vacuum impregnation with thermally shock resistant epoxy resins, have not reached their design fields without significant 'training'. Tough, thermally shock resistant resins[2] are now in use on superconducting coils at the Rutherford Laboratory but the incidence of training does not appear to have been reduced by the use of such resins. Recent experiments at this laboratory[3] on small 'race-track' coils have indicated similar levels of training regardless of the resin type used for impregnation.

It is evident that the cause or causes of the 'training' phenomena are little understood and in such a situation the designers task in attempting to eliminate the effect is difficult if not impossible. The purpose of this report is to detail the evidence for a fundamental parameter of the conductor causing 'training' in superconducting coils.

2 HYPOTHESIS

It is well known[4,5,6] that when materials are strained in a tensile test at low temperatures, the yield (i.e. non-linear) region of the stress/strain curve is not the normal smooth glide type of plastic flow but rather serrations occur in the curve and plastic flow continues with a series of discontinuous yields (fig. 1). The magnitude of the drop in load increases as deformation proceeds and at the same time the frequency of the serrations decreases. Further, the magnitude of the strain 'increase' accompanying each 'drop' in stress also increases. In practice, the actual stress/strain curve obtained is not as 'clean' as the idealised curve shown in figure 1 and a typical graph obtained from a tensile test on a Nb/Ti wire is shown in figure 2; the detailed interpretation of the curve is presented in appendix 1.

The theoretical explanation of serrated yielding has been well documented[5] and the association of heat with unstable plastic flow is now established. In essence, the explanation is that the discontinuities observed in the low temperature stress/strain curve for a metal are caused by a localised temperature rise produced during the deformation, so that if the temperature dependence of the work-hardening is rapid enough, unstable flow can occur. Significant temperature rises[5,6,7] ($\sim$ 60K) have been recorded during such serrations and the theory of serrated yielding requires the heat to be localised for at least the time for the flow to occur. In view of the low temperatures involved, the amount of heat required to produce an appreciable temperature rise is small. Therefore at low temperatures the deformation may be expected to be unstable if the localised heating can produce an appreciable softening of

the material. If the thermal softening caused by heating during deformation is greater than the strain hardening, the specimen rapidly has an applied load greater than necessary for continued deformation at that temperature. The load then drops catastrophically until it is below that required for continued deformation at the current temperature and so plastic flow ceases and the specimen cools to that of the surrounding medium. The specimen is then again loaded elastically until the flow stress is reached, plastic flow and concomitant heating occur and the whole process is repeated.

Mechanical tests[8] on filamentary Nb/Ti conductors and on specimens of Nb/Ti at 4.2 K have shown that serrations appear very early in the stress/strain curve (figures 2 and 3) even at low rates of strain. This fact is predictable from the known poor thermal conductivity of the alloy at 4.2 K. From the foregoing, it is reasonable to assume that a superconducting wire strained at 4.2 K, would be above the superconducting/normal transition temperature each time a serration occurred in the material. This concept of straining and spontaneous heating may now be applied to the superconductive wire in a coil.

Tests have shown that strains in excess of approximately 0.15% will lead to serrations in the conductor. The 'average' strain in a superconducting coil, allowing for stresses induced during cooldown and powering, is likely to amount to less than 0.1%. However, it is likely that 'stress-raisers' in the coil could increase the strain locally on a conductor to exceed the above figure. Such a situation is more likely in a dipole or quadrupole than in a simple solenoid. The homogeneous structure of

the latter is more likely to be amenable to stress analysis and to be free of 'stress-raisers'. This fact alone may account for the lower incidence of training in solenoids than in other coil configurations.

If the situation could arise where strain induced serrations are occurring in the material, it is postulated that the heating from this effect is driving the coil normal locally and therefore causing it to 'train'.

Interest then must be centred on the strain necessary to induce serrated yielding. For any given metal, this strain is directly proportional to the thermal conductivity and is an inverse function of the strain rate. It is difficult to be dogmatic about the strain at the onset of serrated yielding even at a constant strain rate, since for any metal this critical strain may also change with specimen size, shape and environment. It is therefore to be expected that there may be some measure of disagreement between workers in this field who may be using specimens differing in geometry. In the case of Nb/Ti alloys, the important point is that because of the poor thermal conductivity, serrations are induced almost immediately the material is strained beyond the linear elastic region even at low strain rates and the graph presented in figure 3 was obtained at a calculated strain rate of 1.3×10^{-4}/sec.

3 CONCLUSIONS

Much of the observed 'training' behaviour of superconductive coils may be explained in terms of strain induced local heating of the

conductor and concurrent serrated yielding.

It is likely that the relatively high strains assumed in this hypothesis are only achieved in localised areas and possibly result from a lack of homogeneity in the coil. During a tensile test at 4.2 K on a superconducting composite serrations have been induced at strains of less than 0.2% in the composite. It is more difficult to observe serrated yielding in specimens of conductor composed of Nb/Ti in a copper matrix, since it is the Nb/Ti which is serrating at low strains and the copper continues to yield in the normal manner.

Serrations may be induced by straining a specimen in the tensile or compressive mode and tests are underway at the Rutherford Laboratory to examine the validity of this hypothesis.

Finally, it is postulated that a coil which 'trains' reaches its design performance only after yielding of the conductor, possibly induced by stress raisers in the coil configuration.

tb

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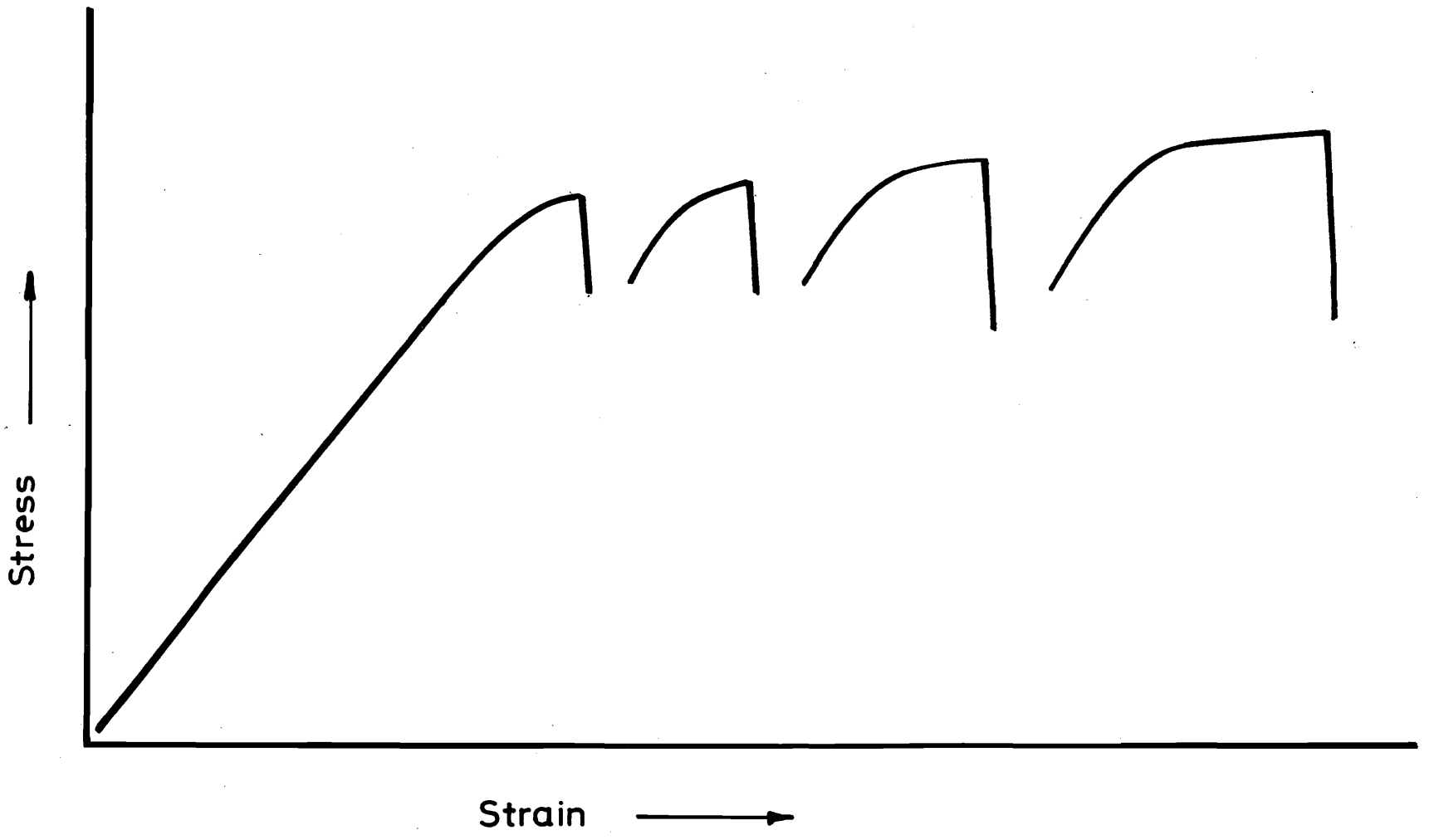

FIGURE 1. DIAGRAMMATIC REPRESENTATION OF SERRATED YIELDING.

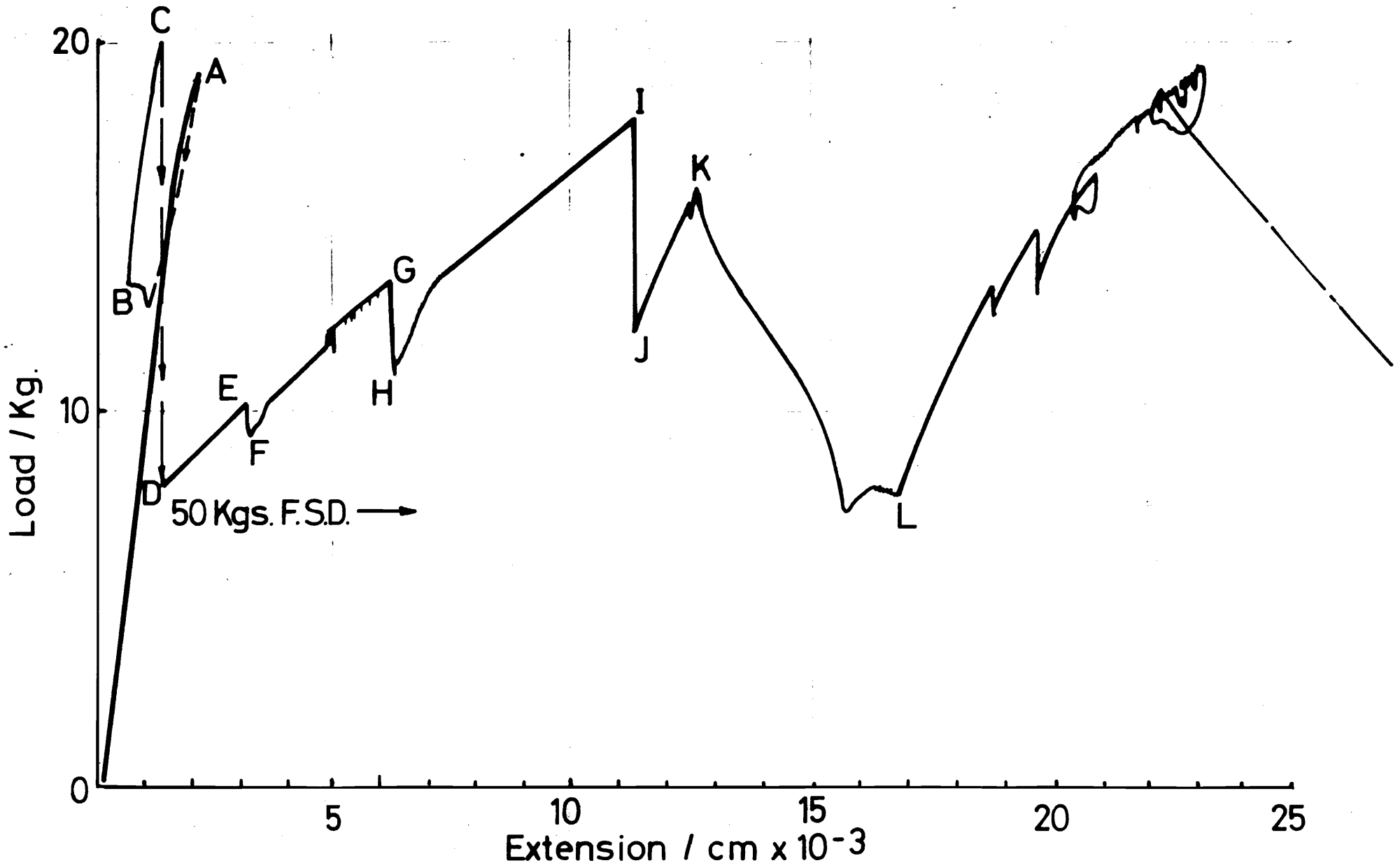

FIG. 2 LOAD/EXTENSION GRAPH FOR Nb/Ti COPPER COMPOSITE.

Matl:- A61 IMI Superconductor 1·07mm dia. cu:sc = 1·35:1.

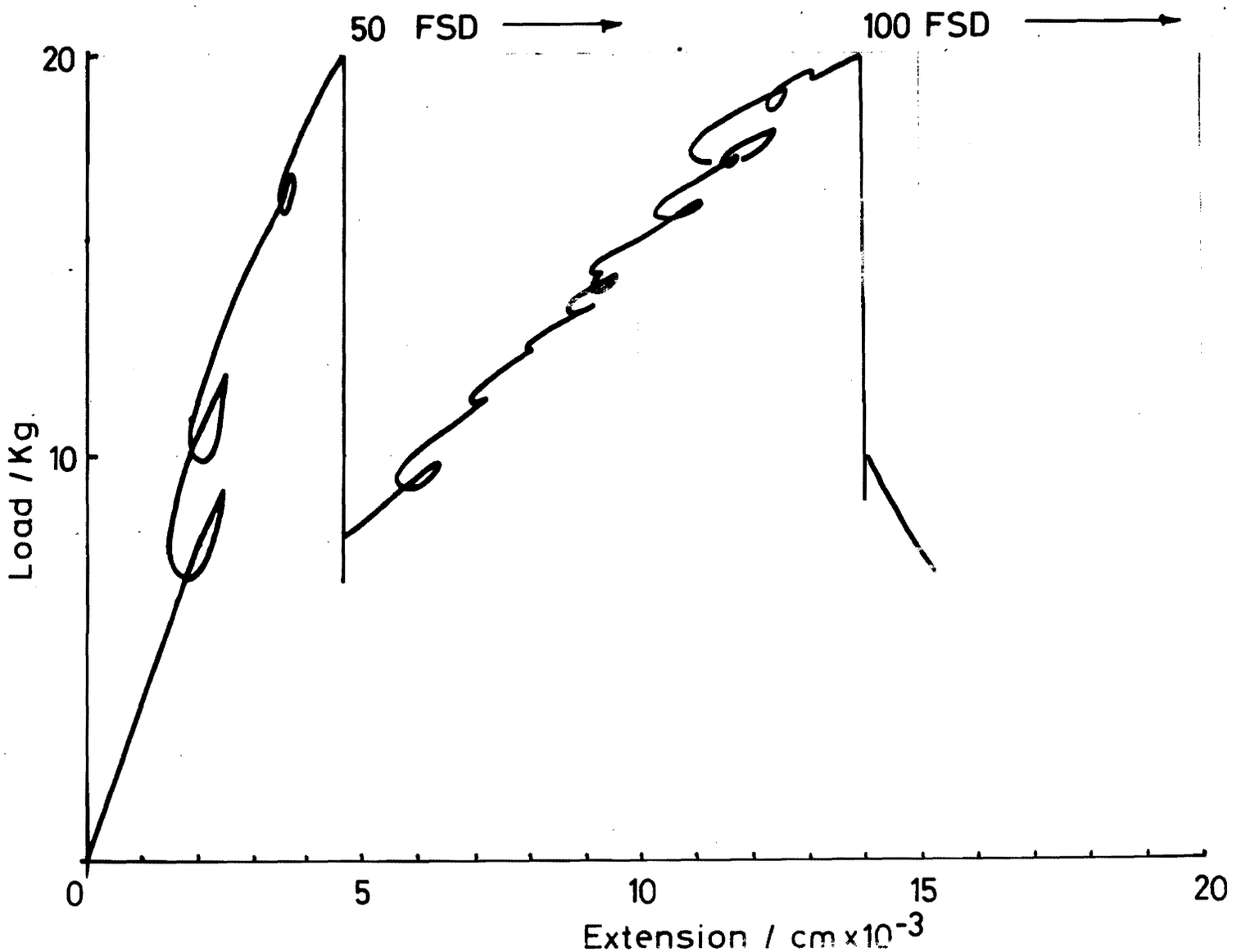

FIG. 3 LOAD / EXTENSION GRAPH FOR Nb/Ti TWISTED FILAMENTS.

Matl:- A61 IMI Superconductor 0·96 mm dia.

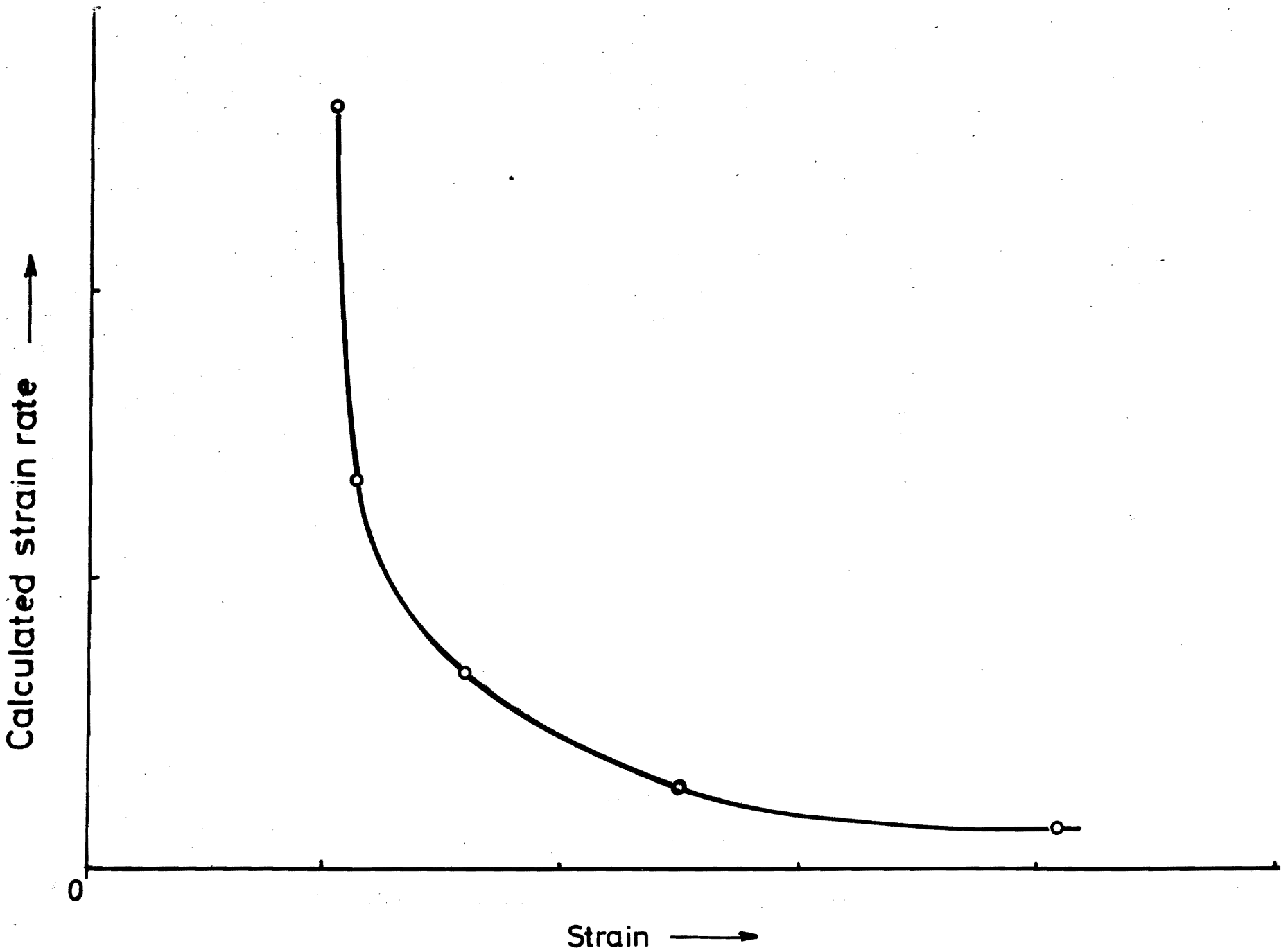

FIGURE 4. EFFECT OF STRAIN RATE ON THE ONSET OF SERRATED YIELDING AT 4·2 K. (DIAGRAMMATIC).

APPENDIX

INTERPRETATION OF LOAD/EXTENTION DATA

For the graphs detailed in figures 2 and 3 of this report, a portal frame strain gauge extensometer was used for the precise measurement of strain. The device is attached to the specimen by a system of knife edges and spring loaded plungers (figure 1) and for the purpose of interpreting the load/extention graph, the specimen gauge length is that defined by the extensometer knife edges.

Since the heating and yielding associated with each serration are localised, such regions may occur either inside or outside the extensometer gauge length. The specimens used to produce the graphs in figures 2 and 3 were nominally 50 mm in gauge length whereas in each case the extensometer gauge length was only nominally 10 mm. It is therefore likely that most serrations would occur outside the gauge length defined by the extensometer.

In figure 2, the first serration occurs at point A, and this results in a decrease in load and predictably in the associated strain, to point B. Less predictably, further serrations (EF, GH, LJ in figure 2) show load drops without a change in strain. It is probable that all these serrations have occurred outside the extensometer gauge length. With the exception of the first serration the decrease in stress in the composite has not resulted in a change in surface strain in the copper. The serration indicated by the points K L (figure 2) has occurred inside the extensometer gauge length and

the permanent change in surface strain is readily apparent. If it is the case that serrations are occurring randomly both inside and outside the extensometer gauge length, this may be regarded as evidence for the localised nature of the heating/serrated yielding effect and for the fact that serrations are not following one after the other in the same point of the specimen.

Figure 3 in the report shows serrated yielding in a series of loops and the strain at the end of a load drop is lower than the strain for an equivalent load before the serration occurred. It is possible that the loops are caused by the speed and response time of the pen of the X-Y recorder being inadequate to faithfully follow the changes in load and strain or the shape may originate from the twisted filamentary nature of the specimen.

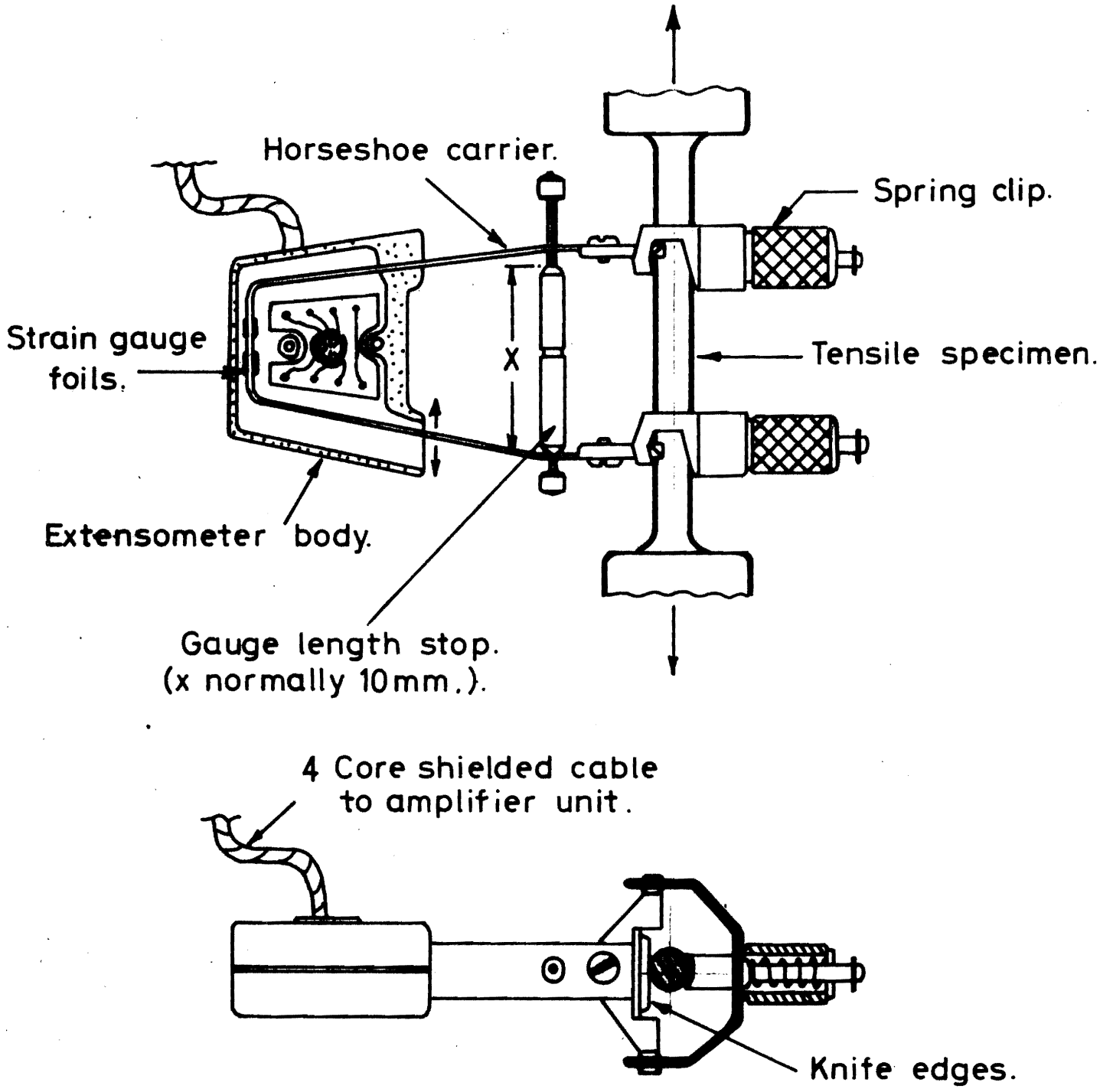

FIG.1 STRAIN-GAUGE EXTENSOMETER.