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MICROSCOPIC CREEP MODELS AND THE INTERPRETATION OF STRESS-DIP TESTS DURING CREEP

PAR

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MODELES MICROSCOPIQUES DE FLUAGE ET INTERPRETATION DES TRANSITOIRES APRES SAUTS DE CONTRAINTE EN FLUAGE

Jean Paul POIRIER - Agent C.E.A.

RESUME :

La technique de "stress-dip" c'est-à-dire de décharge partielle de l'échantillon pendant le fluage stationnaire est très utilisée,en particulier pour mesurer la contrainte interne. On analyse la part importante que jouent les modèles de fluage adoptés dans l'interprétation du transitoire. Quatre cas de figure sont considérés : Fluage controlé par la restauration, fluage thermiquement activé avec obstacles localisés, frottement visqueux, ou les deux. Le rôle joué par les phénomènes anélastiques est également examiné.
La conclusion est que, bien qu'aucune expérience ne mette en cause le concept de contrainte interne, la mesure de celle-ci,par technique de stress-dip repose sur trop d'incertitudes et d'hypothèses pour être vraiment convaincante.

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INTRODUCTION

Among all the experimental techniques currently in use to investigate the mechanisms of high-temperature creep, there are very few which are more controversial than the stress-dip test and which have given rise to a more abundant literature. Needless to say, this state of affairs results in a good deal of confusion.

To the unprejudiced observer there seems to be a striking disproportion between the raw data of the stress-dip test : a transient in a creep curve, and the vast amount of information that the experimenters claim to derive from it. Surely, the results must depend on the more or less clearly stated assumptions that are introduced at various stages, even quite early during the process of apprehending the data and quantitatively describing the transient. The purpose of the present paper is not to present a review of the field, as there are already several good ones (e.g. Bolton 1973, Takeuchi and Argon, 1976); rather it is to attempt a critical analysis of the principal divergent view points, starting from the raw data and examining how they can be described and interpreted in the light of various creep models.

The following problems will be raised (but not necessarily resolved !) :

(a) - Is the reverse strain (negative creep) anelastic or plastic ?

(b) - Is the zero creep rate period due to recovery or is it spurious ?

(c) - Can the existence or inexistence of an internal stress be deduced from stress dip tests ?

(d) - Can stress dip tests allow to determine whether glide is jerky or viscous ?

(e) - Can the internal stress be measured by stress dip tests ?
(which is not at all the same question as (c))

2 - FACTS, ASSUMPTIONS AND MODELS

2.1 Raw experimental data

If an experimenter performs a stress dip test during secondary creep, (s)he is usually presented with two reasonably straight lines with slopes $\dot{\varepsilon}_1$ and $\dot{\varepsilon}_2$ in a ε - t plot, connected by a transient curve.
The creep apparatus is generally assumed to be perfectly elastic, which is a reasonable assumption. If the sensitivity and accuracy of the devices used to record strain and time were extremely high, the most general transient curve could probably be analysed into 4 regions $T_1 \ldots T_i \ldots T_4$, each characterized by the variation $\varepsilon(t)$ and the corresponding quantities $\Delta\varepsilon_i$ and Δt_i (fig. 1).
Now, according to the material investigated, the temperature range and the magnitude of the stress dip $\Delta\sigma$, some of these stages can be missing. Besides, as the sensitivity of the $\Delta\varepsilon$ and Δt measurements is not infinite a stage with a very short $\Delta\varepsilon$ or Δt may be missed and the limits between stages become hazy. The risk is that the cut-up into stages can be strongly influenced by assumptions and models, in other words that one finds and measures what one believes there is.

2.2. Some interpretations of the stages of the transient

We will now examine the most general case of transient (fig.1) and review the models that can be used to interpret the various stages.

a) The stage T_1 corresponding to an instantaneous $\Delta\varepsilon_1$ is always present. There is no doubt that the reverse elastic strain corresponding to the stress drop $\Delta\sigma$ accounts, at least partly, for $\Delta\varepsilon_1$. However, the amount of elastic strain instantaneously recovered depends on the anelasticity of the creep sample. Besides, $\Delta\varepsilon_1$ may also comprise a reverse plastic strain occuring by jerky glide in a time Δt much too short to be measured with the usual equipment.

If $\Delta\varepsilon$ corresponding to a reverse plastic strain is of the order of magnitude of the delayed elastic strain, $\Delta\varepsilon_1$ (if accurately measurable) may be mistakenly considered as an entirely elastic strain.

b) The stage T_2 during which the reverse strain varies in time is very important since momentous conclusions are often drawn from its presence or absence. A strain varying in time must be either anelastic (viscoelastic) or viscous plastic. We only need an operational definition of these phenomena at this point and we will not enter into the underlying physical mechanisms (see § 2.3). Suffice it to say that the anelastic strain is recoverable whereas the plastic strain is not. The difference is best illustrated by loading-unloading cycles in tension at constant strain-rate (Roberts and Brown, 1960 ; Brown and Ekvall, 1962) where the stress strain curve exhibits closed loops in the anelastic domain and open loops in the plastic domain ; however, no such simple criterion is available in the case of a single stress drop during a creep test. The energy dissipation mechanisms which are responsible for internal friction under cyclic stress conditions in the anelastic domain (Roberts and Brown, 1962; Lloyd and Mc Elroy, 1976) are necessarily the same as those accounting for viscosity in plastic microstrain. Obviously then, there is no simple way of connecting stage T_2 to any single mechanism in the absence of additional information.

c) Stage T_3 is a zero creep rate period of duration Δt_3. Such a stage, when it occurs, has been interpreted in two conflicting ways : as a physically meaningful period during which recovery of the structure occurs, allowing creep to proceed once the internal stress has been lowered to the level of the new applied stress (Mitra and Mc Lean, 1966, 1967) or as a spurious phenomenon resulting from the superposition of continued forward creep and reverse anelastic strain (Hart, 1970 ; Lloyd and Mc Elroy, 1974).

d) No consideration has been given to stage T_4 which is most of the time a mere bend in the creep curve between T_3 and the new secondary regime.

2.3 Physical sources of reverse strain upon a stress drop

2.3.1 *Reverse anelastic strain (RAS)*

It is generally agreed that the most significant mechanisms responsible for strain-amplitude dependent, frequency independent internal friction is the bowing out of dislocation segments under alternating stress (Granato and Lücke, 1956 ; Roberts and Brown, 1962).
The same mechanism has been proposed for the elastic after-effect following a stress drop (RAS) by Lloyd and Mc Elroy (1975).
However in this case one must consider only the unbowing of dislocation segments, immobilized in a bowed out configuration, toward a new configuration at reduced stress. For a dissipation of energy to occur there must exist a friction mechanism compelling the dislocations to move in a viscous manner instead of swinging back elastically. At high temperature the dissipative mechanism can be the interaction of dislocations with solute atoms or the climb of dislocations controlled by the formation and migration of jogs (Friedel, Boulanger et Crussard, 1955). Another widely quoted but little known anelastic mechanism is grain-boundary relaxation ; Woirgard (1976) has recently found the same " grain boundary " internal friction peaks in single crystals and in polycrystals and has proposed a theory which accounts for it by an extension of the Friedel *et al.* dislocation climb model.

2.3.2 *Reverse plastic strain (RPS)*

Let us now examine the transient curves consistent with the assumptions of various creep models. Needless to say we will ignore anelasticity throughout this paragraph. We will also assume that recovery does not occur during stages T_1 and T_2. Depending on the nature of the obstacles to dislocation glide, it is possible to divide the high-temperature creep models into two classes (Poirier, 1976 a) :

- Recovery (climb) - controlled creep, where the backward stress of the obstacles is of the nature of a long range internal stress. Creep cannot proceed unless the internal stress is reduced to the level of the applied stress by diffusion- controlled recovery of the substructure.

Thermal agitation does not directly participate in the overcoming of the obstacle and there is no effective stress. Creep of this type is in fact athermal.

- Thermally activated creep, where localized short-range obstacles are superposed to a more or less periodic internal stress field. (Jonas, 1970). Thermal activation directly helps overcoming the obstacles and there is an effective stress defined as the difference between applied stress and internal stress. The obstacles can be very high and far apart and in this case the dislocations have a thermally activated, stress dependent waiting time t_W in front of the obstacle before gliding in a jerky fashion until they are blocked in front of the next obstacle. Such would be the case for cross-slip controlled creep (Friedel, 1964; Poirier, 1976 b) or creep controlled by the thermal unpinning of attractive junctions (Guyot, 1966; Sastry, Luton and Jonas, 1974). The obstacles may also be less important but present at almost every atomic step of the dislocations, "smeared"so to speak,in this case we have truly a friction force and the thermally activated overcoming of this type of obstacle leads to viscous glide (e.g. solute drag or jog drag).

Clearly the two types of obstacles can be present at the same time, but in this case, the RPS must be viscous. We have therefore four cases to examine :

a) Athermal, Recovery-controlled creep (Fig. 2)

There is no viscous drag, hence the glide is jerky between obstacles seen as rather large bumps on the σ_i curve. It is clear from the force distance curve that for an ever so small stress drop $\Delta\sigma$ there will be an instantaneous RPS followed by a zero creep rate period Δt_3 during which σ_i must be lowered. Δt_3 as well as the contribution of the RPS to $\Delta\varepsilon_1$ should depend on $\Delta\sigma$.

b) Thermally activated creep, localized obstacles jerky glide (Fig. 3)

The force distance curve (*) shows that for a stress drop $\Delta\sigma < \sigma_{eff}$ the waiting time is only increased and creep continues forward at a reduced creep rate. There is no RPS. For $\Delta\sigma > \sigma_{eff}$ there is an instantaneous RPS followed by a zero creep rate period during which σ_i must be lowered.

(*) The force-distance curves given here are T = const. curves for creep. The dislocations in equilibrium are figured at a height along the obstacle corresponding to σ_A. The waiting time t_W hence,the creep-rate,$\dot{\varepsilon}$ are determined by the part of the energy that can be furnished by thermal agitation : $\Delta H_0 - \Delta V\sigma_{eff}$. Note the difference with the force-distance curves usually given in the literature, which are curves for an imposed $\dot{\varepsilon}$ (hence t_W), which determines the applied stress.

c) Thermally activated creep, viscous glide (Fig. 4)

The conclusions are the same as in case (b) but here the RPS is not instantaneous and a stage T_2 appears for $\Delta\sigma > \sigma_{eff}$ before the zero creep rate period.

d) Thermally activated creep, localized obstacles and viscous drag (Fig. 5)

The behavior obviously depends on the level of the applied stress and the magnitude of $\Delta\sigma$. If the applied stress is high and $\Delta\sigma$ small the viscous drag is not felt and the situation is comparable to case (b) whereas if the stress is lower and/or $\Delta\sigma$ large the analysis of case (c) should apply. It should be almost impossible to distinguish the very different cases (c) and (d) on the basis of the appearance of the transient curve.

TABLE I : sums up the conclusions for the various cases ;

Creep model	Type of flow	Predicted behavior for :	
		$\Delta\sigma < \sigma_{eff}$ (or small $\Delta\sigma$)	$\Delta\sigma > \sigma_{eff}$ (or large $\Delta\sigma$)
Athermal Recovery-controlled	Jerky	Zero creep	Instantaneous RPS Zero creep
Thermally activated Localized obstacles	Jerky	Forward creep	Instantaneous RPS Zero creep
Thermally activated Smeared obstacles	Viscous	Forward creep	Delayed RPS Zero creep
Thermally activated Both types of obstacles	Jerky or Viscous	Forward creep	Delayed RPS Zero creep

3 - DISCUSSION

The analysis presented above differs from Nix's (1976) approach essentially in the way in which basic concepts are identified and put together : Whereas Nix viewpoint is grounded on the dichotomy : viscous vs jerky glide, we contend that the dichotomy : athermal ($\sigma_{eff} = 0$) vs thermally activated ($\sigma_{eff} > 0$) creep allows a clearer analysis of the processes going on during the stress dip test. This of course does not mean that all the necessary information can be extracted from the transients and this is what we must examine now by addressing the questions listed at the end of § 1.

3.1. - Is the negative creep anelastic or plastic ?

The answer to this question is most probably : Negative creep is both anelastic and plastic in various degrees. Although the current theories have focused on one of these aspects and neglected the other, it is clear that they are not mutually exclusive, as we will try to show by comparing the models proposed by Ahlquist and Nix (1971) and Nix (1976) with the anelastic model proposed be Lloyd and McElroy (1974).

Nix's model is essentially the one presented here as as case (c) (§ 2.3.2) of thermally activated viscous glide : the vast majority of dislocations is mobile, there is forward creep for $\Delta\sigma < \sigma_{eff}$ and negative creep for $\Delta\sigma > \sigma_{eff}$. Negative creep here is a delayed RPS, there is therefore a frictional viscous force acting on the dislocations hence a potential source of anelasticity should a fraction of the dislocations be immobilized and able to unbow.

Lloyd and McElroy assume that the majority of dislocations is immobile and pinned at the junctions of a network. As there is a distribution of segment lengths, there is always a possibility for forward creep is $\Delta\sigma$ is small. The bowed out dislocations can unbow when the stress is dropped and produce RAS. If this is so, there must exist a frictional drag force acting on the dislocations. Clearly this model is one of thermally activated creep with localized and smeared obstacles (case (d), § 2.3.2), but Lloyd and McElroy have neglected the possibility of delayed RPS which is inherent in their model.

As the viscosity responsible for the delayed reverse strain is the same for RAS and RPS, it is certainly not possible to tell one from the other by inspection of the transient.

3.2. - Is the zero creep rate period due to recovery or is it spurious ?

Hart (1970) was the first to propose that the zero creep rate period was due to the superposition of forward creep and reverse anelastic strain; this idea was taken again and treated in more detail by Lloyd and McElroy (1974). It is of course compatible only with creep models where forward creep is permissible for a small $\Delta\sigma$ i.e. thermally activated creep models; however, recovery of internal stress for $\Delta\sigma > \sigma_{eff}$ is also compatible with these models as we have seen and it is certainly difficult to answer the question.

In the case of athermal recovery-controlled creep models (case (a), § 2.3.2), neither forward creep for small $\Delta\sigma$ nor anelasticity sources are built in and there is no clear reason to discard Mitra's and

McLean's (1966) interpretation of a zero creep rate period due to recovery.

3.3. - Can the existence or inexistence of an internal stress be deduced from stress-dip tests ?

Although this is how this question is currently put in the literature, it should be reworded thus : can stress dip tests allow to determine whether $\sigma_{eff} > 0$ or $\sigma_{eff} = 0$, i.e. whether creep is thermally activated or athermal ?

It seems that there is a general belief that if "negative creep" is not observed, then $\sigma_{eff} = 0$; Nix (1976) himself, apparently agrees that the fact that no negative creep has been reported in copper single crystals by Davies *et al.*(1973) supports the view that "negative creep effects are not due to internal stresses" and that the negative creep reported in polycrystals is due to other effects.

Obviously, the term "negative creep" is commonly taken to mean "delayed reverse strain" (be it RPS or RAS). The non-observation of a delayed reverse strain in copper single crystals could certainly prove that the creep is athermal recovery controlled ($\sigma_{eff} = 0$) but it might quite as well prove that creep is thermally activated with jerky flow ($\sigma_{eff} > 0$), then there should be an instantaneous RPS. As a matter of fact, this seems to be precisely the case, since Davies *et al* report an instantaneous contraction greater than the elastic contraction.

So the answer to the question seems to be "no". The presence or absence of "negative creep" tells us nothing about the internal stress.

3.4. - Can stress dip tests allow to determine whether glide is jerky or viscous ?

By now the answer to this question seems easy, if not encouraging : the existence of a delayed negative creep transient obviously points to viscous drag mechanisms, but apart from the fact that such transients may be anelastic in origin, there is also the possibility of having viscous RPS and jerky glide together as in case (d) (§ 3.2.2).

3.5. - Can internal stress be measured by stress-dip tests ?

Although no reported experiment gives the slightest ground to reject the concept of internal stress, the analysis of the stress-dip transient presented above is not conducive to any degree of optimism concerning the reliability of stress dip tests to measure σ_i.

Takeuchi and Argon (1976) recently stated that "simple interpretation of the results of transients in creep experiments are of doubtful validity", and the present analysis is certainly in total agreement with this view. However it is interesting to notice that many reviews of stress-dip experiments (e.g. Nix, 1976) give the impression that different materials should behave in the same fashion during stress dip and that lack of agreement between experiments performed on various metals and alloys is a matter of concern. Considering all the possible mechanisms that may come into play, one should on the contrary be rather suspicious if there was some agreement and this at least should not be considered as ground for pessimism.

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FIGURE CAPTIONS

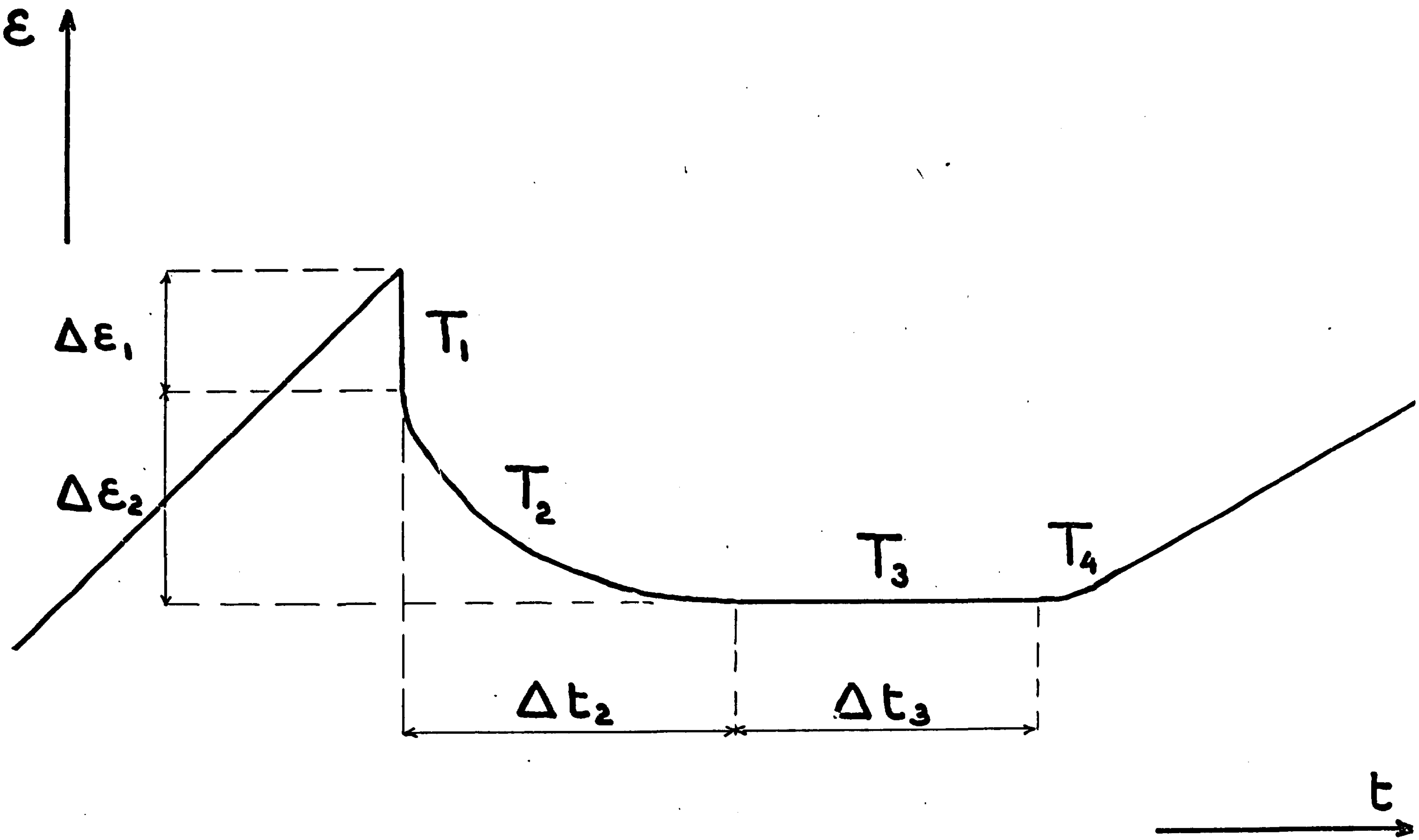
FIG. 1 A reasonable cut-up of the most general transient curve for stress-dip.

FIG. 2 Force-distance curve and predicted stress-dip transient for athermal recovery-controlled creep.

FIG. 3 Force-distance curve and predicted stress-dip transient for thermally activated creep with high localized obstacles.

FIG. 4 Force-distance curve and predicted stress-dip transient for thermally activated creep with viscous drag, without anelasticity.

FIG. 5 Force-distance curve and predicted stress-dip transient for thermally activated creep with high localized obstacles and viscous drag, without anelasticity.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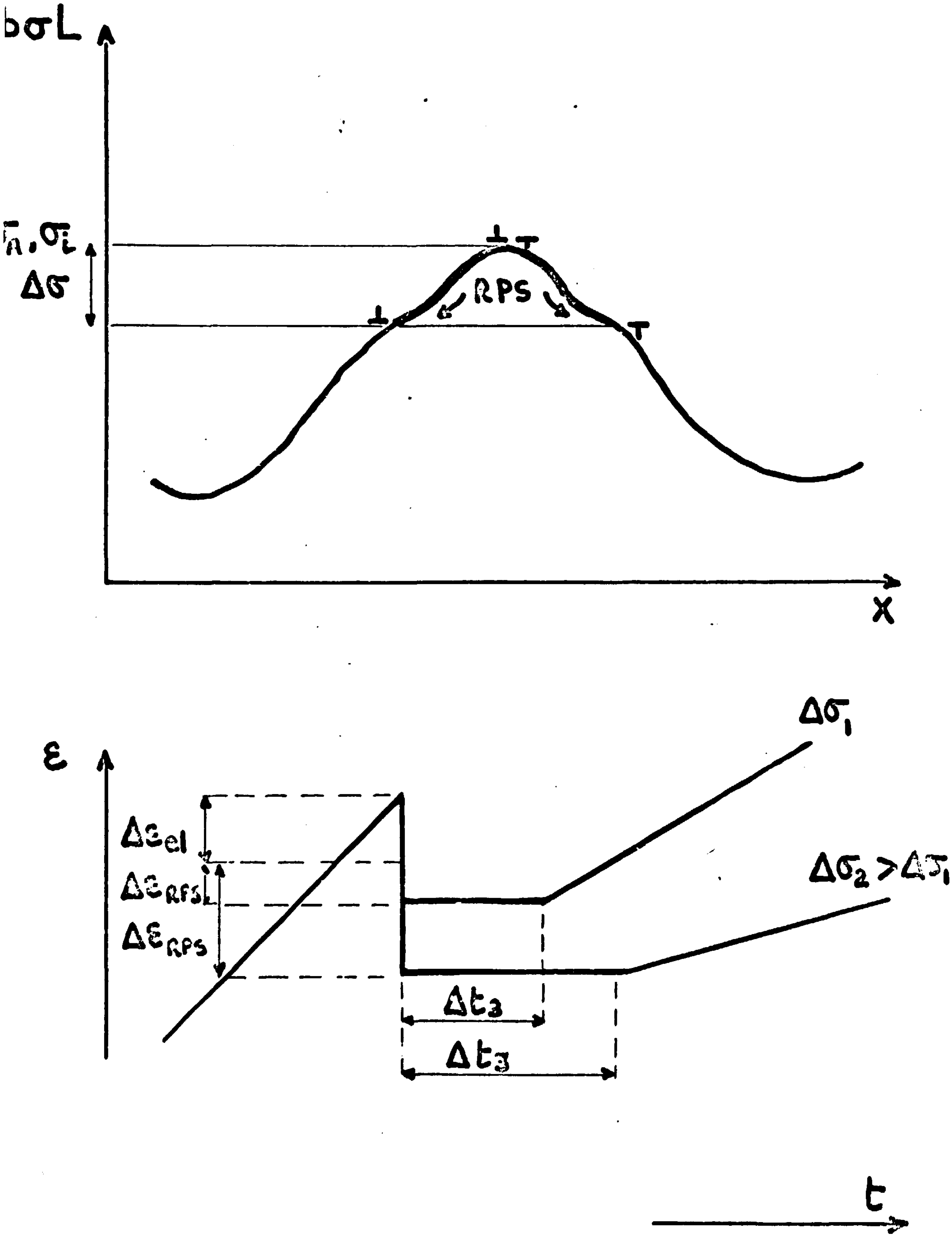
T₂
T₃
T₄
Δt₂
Δt₃
t



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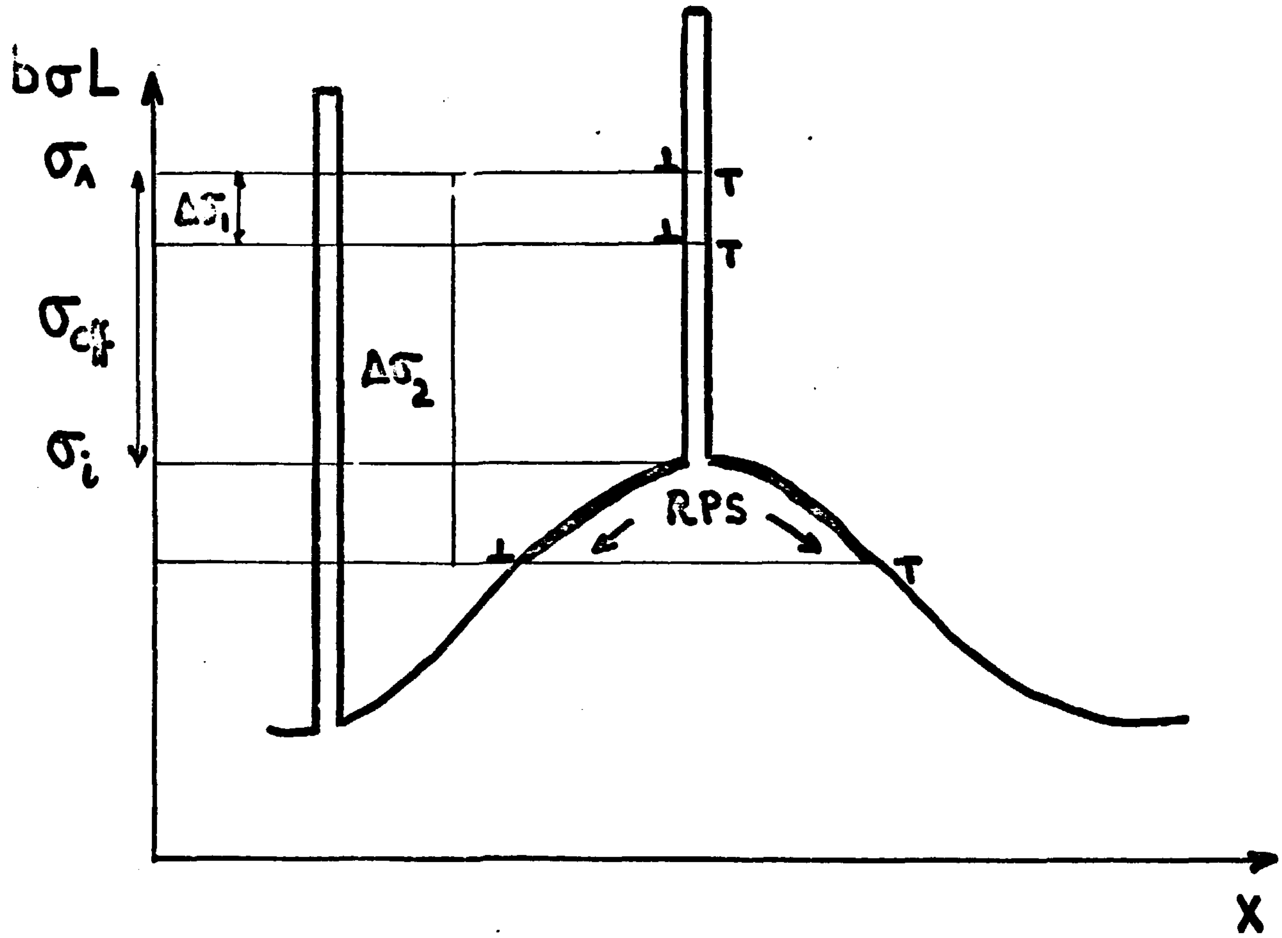
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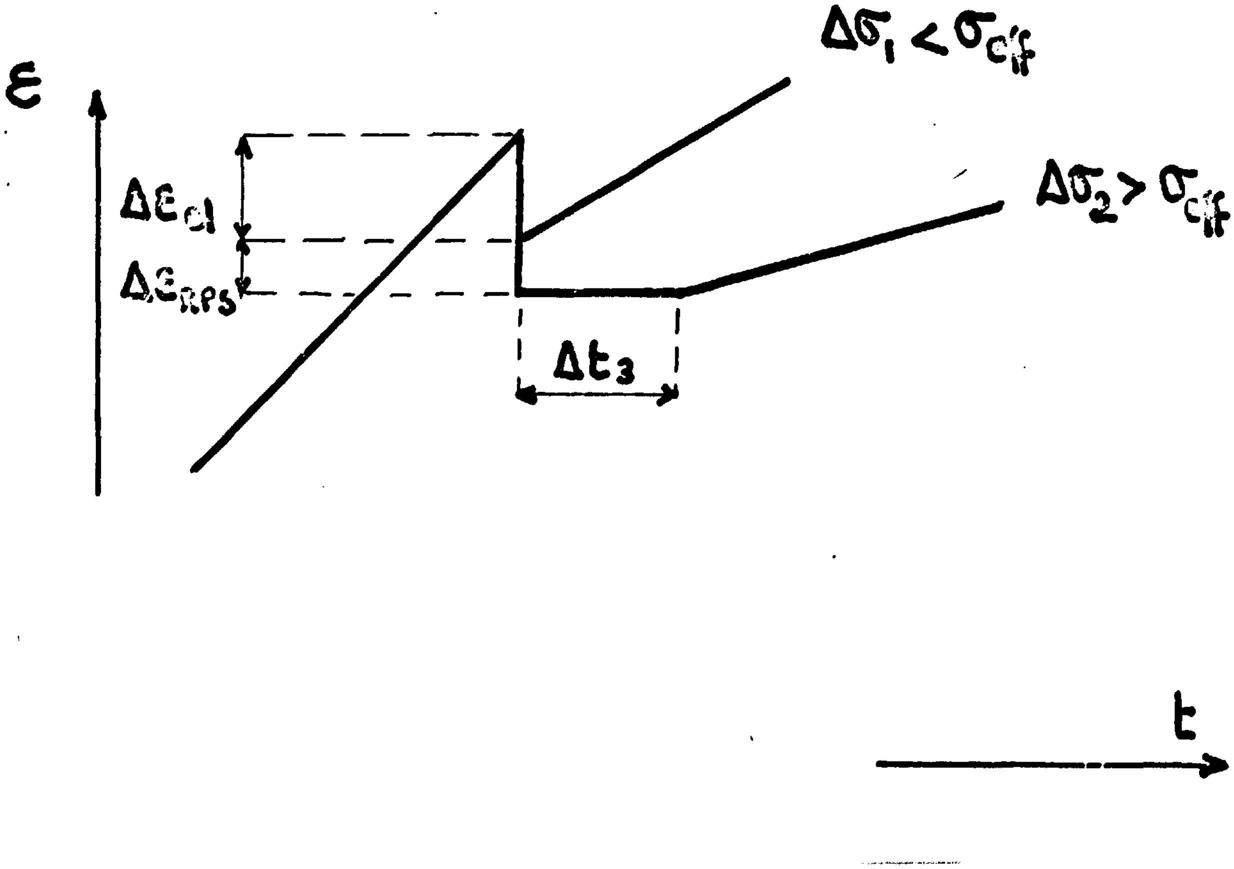
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Δt3
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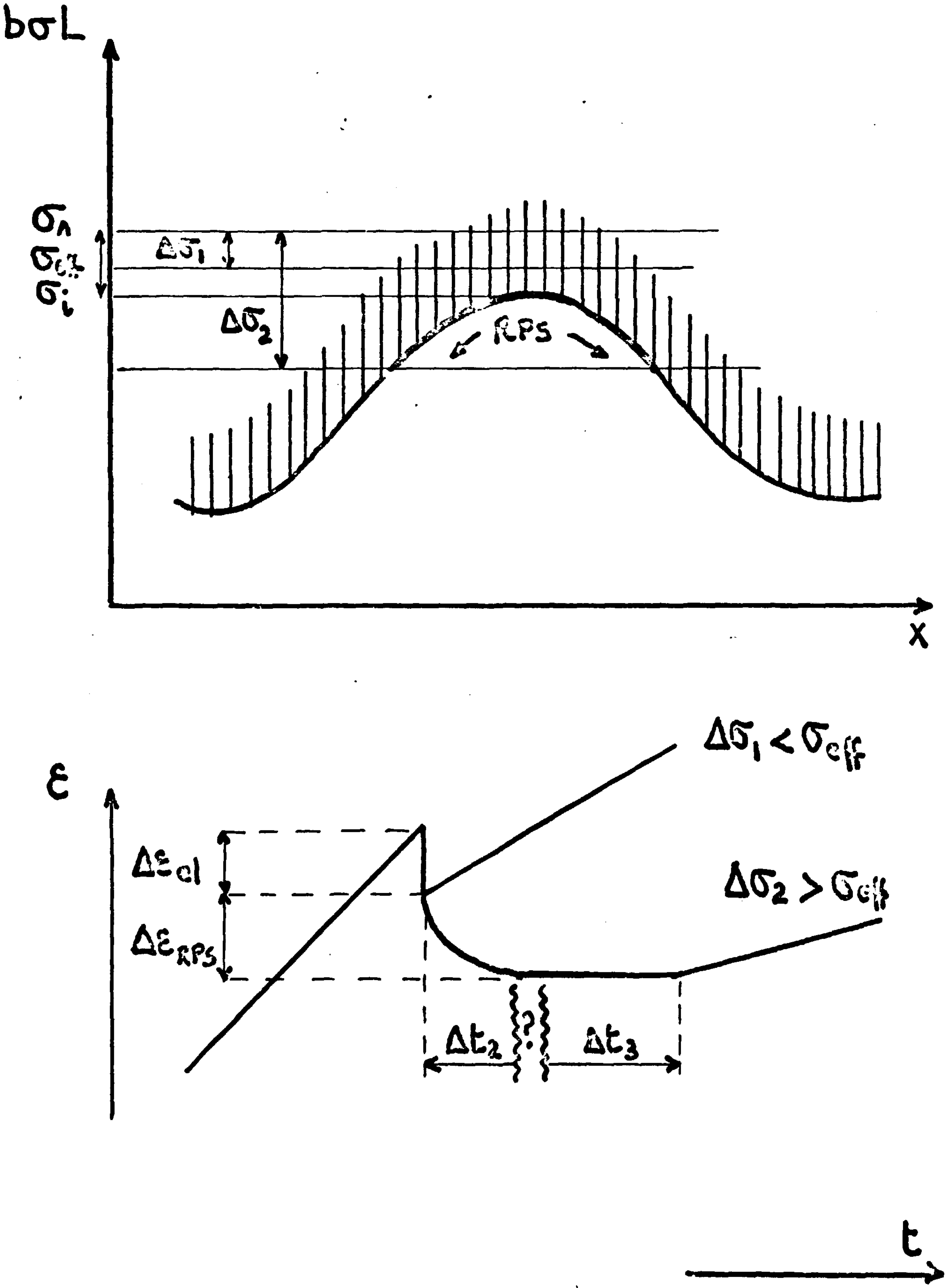
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Δσ_1
Δσ_2
RPS
X
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Δε_RPS
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Δt_3
t

Fig. 4

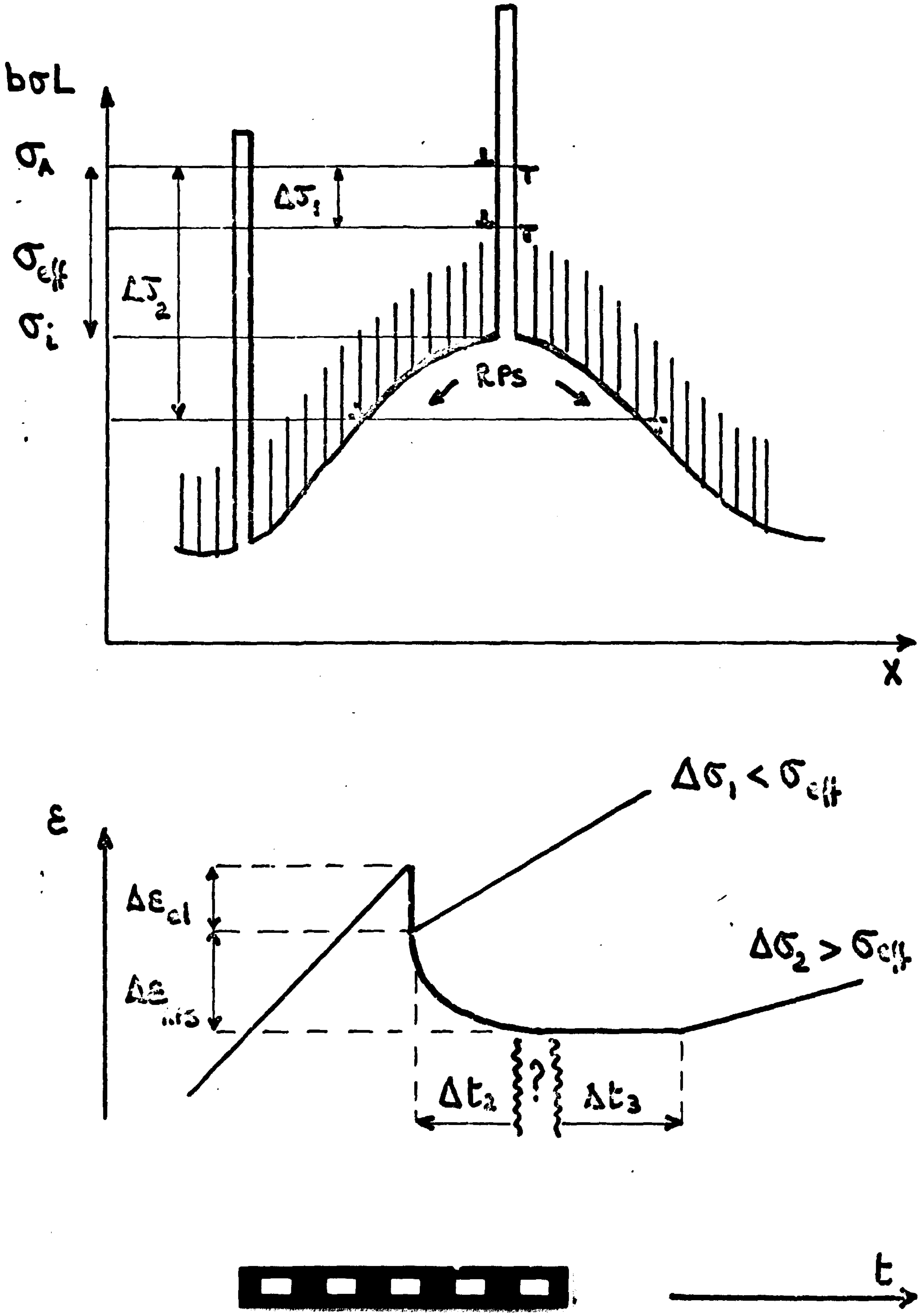

Fig. 5