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DISLOCATION RELAXATION PROCESSES IN METALS

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Abstract.- Original contributions on dislocation relaxation effects, submitted
to this conference, are introduced. The contributions are concerned with
intrinsic dislocation relaxation effects as well as with some dislocation-
point defect interactions, especially hydrogen-dislocation interaction. In
f.c.c. metals, the kink-pair formation model for the Bordoni peaks obtained
further support by new experiments. In b.c.c. metals, by experiments on high
purity and hydrogen charged specimens considerable progress has been achieved
in the understanding of the mechanisms responsible for the numerous relaxation
peaks: a general agreement is obtained for the main intrinsic and hydrogen
induced processes.

1. Introduction.- In this paper we introduce original contributions submitted to this
conference, which are concerned with intrinsic dislocation relaxation effects as well
as with some dislocation-point defect interactions. The original contributions are
quoted here with the names of the authors, other references are given with numbers of
a reference list.

Historically, in f.c.c. metals a clear separation is well established between
intrinsic dislocation processes (Bordoni peaks) and dislocation-point defect inter-
action effects. Mobile dislocation segments may interact with point defects which
are intrinsic and mobile (Hasiguti peaks), extrinsic and mobile (e.g. hydrogen
dragging effects or more general Snoek-Koester peaks, or immobile (unpinning peaks).
Such a classification scheme may be insufficient for an exact definition of a
mechanism, but it may serve as a first guide.

At this conference a considerable number of contributions is concerned with
b.c.c. metals. Here such a clear separation of intrinsic dislocation effects is
partly a problem. Especially in V, Nb, Ta interstitial solute atoms (H,O,N,C) are
always present in various concentration ranges (1-1000 atppm), and ultra-high vacuum
(UHV) techniques are required to reduce the interstitial solute content. In Nb, Ta
the order of 1 atppm interstitial solute concentration can be obtained. Even at such
a low level interaction effects with dislocations may appear. For low temperatures
the interaction with mobile H has to be considered, for high temperatures (T>400 K)
interactions with mobile O, N, C may become important.

Therefore it is much more difficult in b.c.c. metals to distinguish between intrin-
sisic dislocation effects and dislocation-impurity interactions. UHV purification
techniques let achieve considerable progress recently and the intrinsic dislocation processes in b.c.c. metals as well as studies on specific dislocation-point defect interactions has become a major topic of this session.

Intrinsic dislocation relaxation effects in f.c.c. metals (Bordoni peaks) are presently considered as fairly well understood [1]. This is reflected in a lower number of original contributions to this topic. However, the presented papers give answer to some important open questions. Generally speaking, we are in a phase of consolidation of the kink-pair formation model for the Bordoni peaks. Investigations are extended also to hexagonal metals, which show similar behaviour as f.c.c. metals.

A highlight of our session certainly is the presentation of results, obtained with a new experimental technique, which can deliver directly information on the underlying mechanism of the relaxation effect (Gremaud, Benoit).

Some contributions are concerned with extreme materials. One paper deals with solid He\textsuperscript{3}, which exists under high pressure at ultra-low temperatures in a b.c.c. structure, where dislocation effects have been studied (Iwasa, Saito, Suzuki). Less extrem, but still a challenge for the experimentalist are investigations on alkali metal single crystals, on which systematic studies on dislocation relaxation effects have been presented (Hammerschmidt, Kirchner, Schoeck).

Several papers are concerned with hydrogen-dislocation interactions in metals and alloys of different structure, partly by techniques sensitive to surface conditions and with quite different intentions.

We mention also a paper on fatigue in Cu studied by internal friction technique (Mizubayachi, Okuda).

In the remaining part of this paper we will review some new result obtained on b.c.c. and f.c.c. metals.

2. Dislocation relaxation peaks in b.c.c. metals

2.1 Nomenclature.- Chambers [2] called the peaks $\alpha, \beta, \gamma$ in the order of increasing temperature, where $\alpha$ and $\gamma$ were considered as intrinsic dislocation relaxation peaks, $\beta$ as due to dislocation-point defect interactions. Later $\alpha'$ was observed as a low temperature subpeak of $\alpha$.

The Grenoble group introduced further $\beta_\alpha$ or $\beta_\gamma$ for indicating interaction effects between dislocation segments mobile in the $\alpha$ or $\gamma$ regime respectively and interacting with interstitial solute atoms (H,O,N,C), and $\beta_1, \beta_2$ for interaction processes with intrinsic point defects.

Three remarks should be added: (1) The $\alpha$ peak in Mo (Grau, Schultz), which can be studied in high purity samples in an convenient temperature regime, has been separated in 4 subpeaks, called $\alpha_1, \ldots, \alpha_4$ (in the order of decreasing temperature), (2) In V, Nb, Ta the peaks called "$\alpha$" in the past are due to hydrogen decorated dislocation segments (see [3], Ritchie's review; Maul, Schultz; Okuda, Mizubayashi et al.). (3) Ritchie in his review suggests to preserve $\alpha'$ for geometrical kink migration in screw components (GKM(\theta)), and $\alpha$ for kink-pair formation in non screws (KPF(\perp)).
2.2 Low temperature dislocation relaxation effects in b.c.c. metals.- Dislocation effects free from interference with H solute atoms were studied in detail in Fe and Mo. One observes in both metals a complex $\alpha$ peak, in Fe usually 2 subpeaks are reported, in Mo there exist distinctly more than 2, probably 4 subpeaks [4]. A $\beta$ process, related to intrinsic point defects, appears in Mo as a high temperature shoulder of $\alpha$. The $\beta$ process in Fe shows an evolution and finally a transformation into peak $\alpha$ in the course of annealing [5]. The characteristic influence of annealing in the temperature regime of stage III recovery (point defect recovery) as reported in [5] can be seen more or less clearly in all b.c.c. metals, investigated so far [6].

The $\beta$ peaks are considered as the analogous to the Haseguti peaks in f.c.c. metals. They require the presence of intrinsic atomic defects, however, less is known for the $\beta$ peaks. Here is an open field for the future. For an deeper understanding one has to consider the mobility of point defects in b.c.c. metals. Below we give the temperatures for the onset of defect mobility for some b.c.c. metals: Fe (125 K, 250 K), Mo (35 K/500 K), W (27 K/800 K), Nb (<8 K, 250 K), Ta (<8 K, 300 K). The indicated temperatures are recovery temperatures for point defects created by irradiation [7]. It should be noted that in terms of a two-interstitial model it is expected that plastic deformation creates only interstitial atoms which become mobile at higher temperatures, in the so called stage III (the higher temperature indicated above). Whereas in a one-interstitial model deformation induced interstitial atoms should migrate at the lower temperature, indicated above. The reader may note that defect mobility in Fe starts at 125 K, in Nb below 8 K. A critical examination of the evolution of the low temperature dislocation internal friction peaks will be interesting.

We turn shortly to the subpeaks of $\alpha$. In Mo, activation parameters, especially activation volumes (for details see [4]) are compatible with the following interpretation: $\alpha_1$-KPF ($\perp$), $\alpha_3$-KPF ($\perp$), $\alpha_4$-GKM (0) for two different geometrical kinks, e.g. $K^+$ and $K^-$ [8].

In Fe two processes of $\alpha$ are separated. A general view similar as in Mo (GKM(0) and KPF ($\perp$)) has been obtained by Astié, Peyrade, Groh. However, Magalas, Moser, have not found support for a GKM component. Microdeformation results confirm in Fe that a main component of $\alpha$ is due to KPF ($\perp$) (San Juan, No, Fantozzi, Esnouf, Vanoni). Magalas, Moser suggest that dislocations with different Burgers' vectors may be responsible for the substructure of $\alpha$.

In V, Nb, Ta small amounts of hydrogen ($\geq$ 1 atppm) create H-Snoek-Koester peaks, which were called "$\alpha$ peaks" in the past, and which mask the intrinsic dislocation relaxation effects. It is hoped that the detailed investigations of Maul et al. [3] on Nb with controlled amounts of H will end a long standing controversy concerning this point. This view is confirmed by Okuda, Mizubayachi, Kuramochi et al. Still open is a final understanding of the combined action of H and O on the relaxation strength and the fine structure of the interaction peaks.
2.3 High temperature peaks in b.c.c. metals.- There is general agreement to relate the γ peak to KPF (θ), i.e. to correspond to the phenomenon controlling the low temperature plasticity of b.c.c. metals. The γ peak is studied in Ta (Rodrian, Schultz), Mo (Grau, Schultz), Nb (DeLima, Benoit), Fe (Astié, Peyrade, Groh) and presents very closed characteristics: its temperature is near the knee temperature of the flow stress-temperature curve, its width is near the Debye width and it shows a tendency to anneal out quickly. In Nb [9] and Fe [10] the instability of the γ peak is studied in detail and it is shown that it is connected with the instability of the screw network. Long straight screw dislocations, as present after low temperature deformation, are expected to bow out under the influence of internal stresses, as soon as the temperature of the γ peak is reached. Thereby lowering the length of screw components (Astié et al. [10]). Experiments on Mo [4] are also in line with these suggestions and indicate the reduction of screw components as well as of internal stresses in the γ regime. The situation in Ta [11] is more complicated. At the peak temperature O solute atoms become mobile and pinning effects interfere with changes of the screw dislocation structure. A subpeak, γ₂ is stable in the presence of O solute atoms and Rodrian [9] gives arguments that γ₂ is due to GKM (θ), where the kinks are decorated with mobile oxygen atoms.

A γ peak can be observed also in K (Hammerschmid, Kirchner, Schoeck) and these observations support the idea that the specific properties of screw dislocations are of crystallographic origin and not a phenomenon preserved to transition metals.

Some results on the Snoek-Koester peak (SK peak) of O or C are presented. Here an examination of a recent theory by Seeger [12] is of interest. Up to now the experimental results presented are not detailed enough to give a final evaluation. For Ta-O (Rodrian, Schultz) agreement or at least consistency with the theoretical predictions has been obtained. For Fe-C, Magalas, Moser could not find agreement with Seeger's predictions. It should be noticed that Rodrian for Ta-O used small impurity concentrations (25 atppm O), whereas Magalas et al. worked in range of high concentrations (1000 atppm C). It is interesting to note that Magalas et al. confirm that the SK peak develops after heating to 600 K, supporting the suggestion of Mondino, Seeger [13] on carbon-vacancy pair dissociation.

2.4 Conclusions for b.c.c. metals.- At this conference it appears clearly that a characteristic relaxation spectrum can be proposed for dislocations in b.c.c. metals: - KPF on non-screw dislocations is located at low temperatures with H=10⁻² μ b³ (H activation enthalpy, μ shear modulus, b Burgers vector) - KPF on screw dislocations appears near the knee temperature of the flow stress-temperature curve with H=10⁻¹ μ b³
- GKM peaks are located at low temperatures at the low temperature side of the KPF peak on non-screws. Here further investigations will be appreciated.

- Interaction peaks between H and dislocation segments, (H-Snoek-Koester peaks), appear at intermediate temperatures. In V, Nb, Ta these peaks very often dominate the low temperature spectrum. The Snoek-Koester peaks due to O, N, C interstitial solute atoms require further systematic observations.

- At lowest temperatures, below 10 K, still mobile dislocation segments are present, probably geometrical kinks in non-screw dislocations.

3. Dislocation relaxation peaks in f.c.c. metals.- In Cu and dilute Cu-Au alloys, Schulz and Lenz separate an ultrasonic attenuation (U.S.A.) spectrum with different components due to dislocation resonance, KPF and phonon electron interaction. They find the 2 Bordoni peaks in the 10-50 MHz range and confirm in this range the well-known values $H \approx 0.11$ eV and $\tau_0 = 10^{-12}$ s for the main peak. Lauzier and Minier investigate the substructure of the Bordoni peak in Cu, with the help of electron irradiations and electron microscopic observations and propose that the width of the Bordoni peaks cannot be explained only by a $H$ or $\tau_0$ distribution but must include relaxation of different types of dislocations as suggested by Thompson and Holmes [14]. These results are important also for point defect studies in irradiated metals, where dislocations are used as a probe for migrating defects.

A new experimental technique using U.S.A. measurements during low frequency straining of the specimen is presented by Gremaud and Benoit: they confirm that the Bordoni relaxation in Al must be associated with KPF on dislocations. Direct measurements of the internal stress in strained Al specimens, by dip test method, are performed by Chicois, Hamel, Fougères, Esnouf, Fantozzi, Perez; they confirm the direct amplitude correlation between the internal stress and the Bordoni relaxation i.e. the Paré condition.

By a study on deformed and H charged Ni, Tanaka, Atsumi, Yamada, show that H develops a H-dislocation interaction peak at the expense of the Bordoni peak. These two peaks seem to be similar to the X and Y peaks shown by the experiments of Besson and Boch [15], confirming that the lower temperature peak is the composed Bordoni peak (Y) and the other (X) an extrinsic peak. The work of Seyed Reihani, Esnouf, Fantozzi, Revel, on Mg with different purities, show clearly that the pure Mg spectrum is very similar as the Al spectrum after deformation, on the contrary with the large peak observed in less pure Mg; this large peak is caused by dislocation depinning.

As a conclusion the present studies on f.c.c. metals confirm the main characteristics of the Bordoni relaxation peaks. F.c.c. metals (including Ni) and h.c.p. metals seem to show an uniform spectrum with 2 Bordoni relaxation peaks located at low temperature, but experiments on other (than Mg) h.c.p. metals of high purity are needed to confirm this point of view. The interpretation of Bordoni relaxation as KPF on dislocations is well confirmed, but perhaps attention must be focussed on the different types of dislocations concerned with Bordoni relaxation peaks.
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