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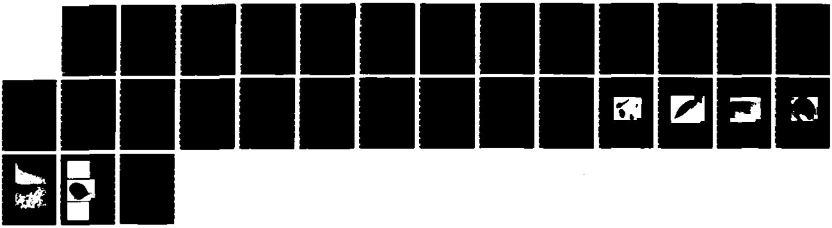

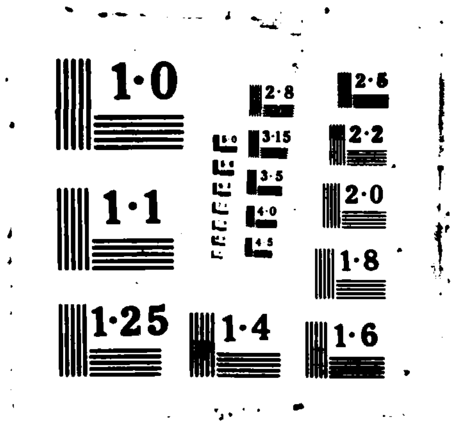
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Fundamental Studies of Beta Phase Decomposition Modes in Titanium Alloys

by

H. I. Aaronson, Principal Investigator
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T. Furuhara, Graduate Student
H. J. Lee, Graduate Student
Y. Mou, Graduate Student

for the period
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Fundamental Studies of Beta Phase Decomposition Modes in Titanium Alloys

H. I. Aaronson, A. M. Dalley, T. Furuhara,
H. J. Lee and Y. Mou

ABSTRACT

A TEM investigation of the bainite reaction in Ti-X alloys has been completed. Particularly in a Ti-Cr alloy, but also in other Ti-X systems, both the eutectoid alpha and the eutectoid intermetallic compound components of bainite have been shown to grow by means of the ledge mechanism. Unlike pearlite (as recently demonstrated by Hackney and Shiflet), the systems of ledges on the two eutectoid phases are physically independent. A theoretical treatment of the diffusional growth of two eutectoid phases has been made following an analysis due to Hillert but incorporating growth by the ledge mechanism and permitting independence of the growth of the two product phases. This analysis showed that, when the equilibrium proportions of the two precipitate phases develop, they can only grow at the same rate when h/λ (h = ledge height and λ = inter-ledge spacing) is the same on both. This situation does not appear to obtain in our Ti-Cr bainite (when a correction is made for the non-equilibrium proportions of alpha and $TiCr_2$ formed) but does in pearlite because (Hackney and Shiflet showed) the ferrite and cementite phases share the same set of growth ledges. Hence a fundamental distinction has been established between the pearlite reaction and the microstructurally-defined bainite reaction. Studies of surface relief effects associated with proeutectoid alpha plates in a Ti-Cr alloy have shown that c. 80% of these plates yield tent-shaped reliefs while the remainder produce the invariant plane strain relief which is the only one acceptable for a martensitic transformation. TEM experiments showed that all proeutectoid alpha plates in contact with the free surface are monocrystals in their thickness direction; hence the tent-shaped reliefs cannot be the result of two plates having formed back-to-back. All alpha plates studied were formed above T_o. Hence not even those yielding an IPS relief can have formed martensitically. TEM studies on grain boundary alpha

allotriomorphs formed in a Ti-Cr alloy, still in their early stages, have shown that both the boundary between an allotriomorph and the beta grain with respect to which the allotriomorph has a Burgers orientation relationship *and* the boundary between the allotriomorph and the adjacent beta grain to which the allotriomorph is apparently irrationally oriented have a ledged structure. These observations are in accord with predictions based upon nucleation theory but are in marked disagreement with current ideas on the interfacial structure of allotriomorphs. The ledges are closely spaced, with λ/h being only c. 3-5. Hence a theoretical analyses applied to determine the growth mechanism of grain boundary allotriomorphs will have to be couched in terms of ledgewise growth instead of assuming that the allotriomorphs have a disordered structure, as is presently the general practice.

1. INTRODUCTION

This program is primarily concerned with fundamental studies of the crystallography, morphology and kinetics of the proeutectoid alpha and the bainite reactions in Ti-X alloys. Interest is retained, however, in the massive mode of alpha formation, particularly in Ti-X systems, but also and increasingly in terms of the fundamental aspects of this transformation mode. By the term "bainite" we mean the product of eutectoid decomposition in a non-lamellar mode [1, 2]. Other definitions of bainite are currently in active use; critical consideration of these definitions forms an important part of the present program.

Unexpectedly, 1986 again turned out to be a major transition year for this program. A few months later than expected, Hwack Joo Lee finished his Ph.D. research on the bainite reaction in Ti-X alloys and departed in April, 1986. Mr. Neeraj Nityanand, a new student on this program whose Ph.D. thesis was intended to deal with the interfacial structure and crystallographic aspects of the $\beta \rightarrow \zeta_m$ transformation in a Ag-26 a/o Al alloy, failed his Ph.D. Qualifying Examination. He was immediately dropped from this program, and shortly afterwards abandoned his graduate studies in Metallurgical Engineering and Materials Science. He has now been replaced by Mr. Yiwen Mou, a professor at Chongqing University in Emei, Sichuan, PRC, who will seek his Ph.D. and undertake the thesis previously attempted by Mr. Nityanand. Very recently, the P.I. was dismayed to learn that Miss Amber Dalley has also decided to terminate her graduate studies. Miss Dalley was being supported by a Fellowship wholly funded by the MEMS Department of CMU, though her supplies and equipment were provided by this AFOSR grant. She has contributed valuably to this program and will be much missed. Her research, on the influence of beta grain size upon Widmanstatten sideplate formation in Ti-Cr alloys, cannot now be continued under this program. However, two closely related investigations on an alloy of direct USAF interest, Ti-6% Al-4% V, are in progress in collaboration with Dr. F. H. Froes and his group at Wright-Patterson AFB and should be completed shortly. In the meantime, Miss Dalley will spend the balance of the present (Spring) semester at CMU, working with Mr. Furuhara to expedite development of his program on grain boundary alpha allotriomorphs in a Ti-Cr alloy.

Both research programs now being pursued by graduate students emphasize the role of crystallography in phase transformations, especially the structure of the interphase boundaries whose migration accomplishes these transformations. Mr. Mou will be focussing upon the structure of massive:matrix boundaries in a Ag-Al alloy. (This transformation serves as a "stand-in" for the Ti-Si, Ti-Ag and Ti-Au alloys in which the $\beta \rightarrow \alpha_m$ massive transformation occurs, since the beta matrix unfortunately transforms to martensite when these alloys are quenched to room temperature, thereby preventing TEM studies of the $\beta:\alpha_m$ boundary structure.) Mr. Furuhara will be concerned with the interphase boundary structure of grain boundary alpha allotriomorphs in Ti-Cr alloys. Both investigations are intended to have significance well beyond that of the alloy systems being used as models: we seek general laws, and feel that the alloys being employed are particularly suitable vehicles for deducing them.

2. THE BAINITE REACTION IN TI-X ALLOYS

2.1 Introductory Remarks

This research constituted the Ph.D. thesis of Dr. Hwack Joo Lee, who has since returned to Korea and is now a member of the Technical Research Laboratory of Pohang Iron and Steel Co., Ltd., Pohang, Republic of Korea. At the time this report was prepared, we were completing preparation of the five papers derived from this thesis for submission for publication. Hence in the following subsections we reproduce the abstracts of these papers. The complete papers are included in this report as Appendices.

2.2 Mechanisms of the Bainite (Non-Lamellar Eutectoid) Reaction and a Fundamental Distinction between the Bainite and the Pearlite (Lamellar Eutectoid) Reactions

(This paper is reproduced in Appendix I. It is being submitted to Acta Metallurgica.)

A Hillert analysis of the edgewise growth of pearlite is modified by assuming that α and β, the products of the eutectoid decomposition of a γ phase matrix, grow by means of the ledge mechanism and by temporarily decoupling α and β growth kinetics. When equilibrium proportions of α and β form, the growth rates of the two product phases, G_α and G_β, are found to be equal only when $h_\alpha/\lambda_\alpha = h_\beta/\lambda_\beta$, where h = ledge height and λ = inter-ledge spacing. This result reproduces the Hackney-Shiflet observation that ferrite and cementite plates in pearlite formed in an Fe-C-Mn alloy lengthen by means of shared growth ledges. When $h_\alpha/\lambda_\alpha \neq h_\beta/\lambda_\beta$, $G_\alpha \neq G_\beta$; hence one product phase, say, α, grows more rapidly than β and usually interrupts contact between β and γ. Thus the repeated re-nucleation of β crystals at α:γ boundaries is required. This result is consistent with the Lee-Aaronson observations that the ledge structure on eutectoid α crystals is different from that on eutectoid $TiCr_2$ crystals in bainite formed in a hypereutectoid Ti-Cr alloy. This interfacial structure criterion for eutectoid decomposition by the microstructural bainite mechanism provides a basis for explaining the very wide variations in the microstructure of bainite which can develop in different alloy systems and even within a particular alloy. The external morphologies of bainite usually observed are concluded to derive from the morphology of the proeutectoid crystals serving as their "substrate". The much less frequently found nodular morphology, which is roughly hemispherical at grain boundaries and spherical when nucleated intragranularly, is proposed to be the true or "intrinsic" external morphology of bainite, and to appear only in the absence of appreciable intervention by the proeutectoid phase in the development of the bainite structure.

2.3 Morphology, Crystallography, Growth Kinetics and Mechanism of Bainite Nodules in a Hypereutectoid Ti-25 w/o Cr Alloy

(This paper is reproduced in Appendix II. It is being submitted to Acta Metallurgica.)

The formation of bainite nodules in a hypereutectoid Ti-25 w/o Cr alloy has been investigated with optical and transmission electron microscopy. These nodules are approximately hemispherical when formed in the grain boundary region and about spherical when developed intragranularly. They consist of a dispersion of eutectoid $TiCr_2$ in eutectoid α. The $TiCr_2$ crystals are observed to nucleate at eutectoid $\alpha:\beta$ boundaries. During subsequent growth they are eventually enveloped by the adjacent eutectoid α and must thus be repeatedly re-nucleated. Unlike pearlite, $TiCr_2$ crystals in a given nodule may have different orientations. Both eutectoid $\alpha:\beta$ and eutectoid $TiCr_2:\beta$ boundaries are partially coherent, containing both misfit dislocations and ledges. Also unlike pearlite (vide current studies by Hackney and Shiflet in Fe-C-Mn), the ledge structures of eutectoid α and eutectoid $TiCr_2$ develop independently. Their growth directions are different and their height and average inter-ledge spacing may also differ in a given bainite nodule. Growth kinetics measured at four temperatures in the range 938° - 848°K are consistent with both interdiffusion between α and $TiCr_2$ during ledgewise growth, somewhat assisted (especially at lower temperatures) by interphase boundary diffusion, and independent, volume diffusion-controlled growth of eutectoid α by the ledge mechanism.

2.4 Eutectoid Decomposition Mechanisms in Hypoeutectoid Ti-X Alloys

(This paper is reproduced in Appendix III. It is being submitted to the Journal of Materials Science.)

A TEM study has been made of the bainite reaction in five hypoeutectoid Ti-X alloys, where X was successively Co, Cr, Cu, Fe and Ni. Rational orientation relationships were demonstrated amongst eutectoid α, eutectoid intermetallic compound and the β matrix in Ti-Ni, Ti-Co and Ti-Cr. Formation of Ti_2Co at α:β boundaries was observed. Eutectoid α in bainite was found to be slightly misoriented with respect to proeutectoid α, indicating that it is separately nucleated, perhaps sympathetically, rather than the result of the continued growth of proeutectoid α. Eutectoid Ti_2Co and Ti_2Cu crystals in bainite were approximately equiaxed whereas $Ti\text{-}Cr_2$ crystals were elongated, a result ascribed to a ledge height-to-spacing ratio h/λ at intermetallic compound crystal:β boundaries approaching that of eutectoid α:β boundaries in TiCr but not in the other two systems. In the Ti-Fe alloy, eutectoid α and eutectoid TiFe were directly observed to have ledged interphase boundaries with their β matrix, but with different inter-ledge spacings and growth directions. Observation of pearlite lamellae growing normal to the broad faces of proeutectoid α plates in the Ti-Ni alloy indicates that this mode of eutectoid decomposition, like that of bainite, can develop from partially coherent interphase boundaries. The suggestion was offered that pearlite forms when λ approaches h at the nucleating proeutectoid α:β interface and that bainite develops when $\lambda >>> h$ at this interface.

2.5 Re-examination of a Critical Experiment on Conditions for Formation of Bainite and Pearlite

(This paper is reproduced in Appendix IV. It is being submitted to Acta Metallurgica.)

Diebold, Aaronson and Franti have observed that the product of $\beta \rightarrow \alpha + Ti_2Ni$ eutectoid decomposition in a Ti-6.2 w/o Ni alloy changes from bainite to what appeared to be degenerate pearlite when transformation was preceeded by severe deformation at room temperature and then recrystallization in the $\alpha + \beta$ region. These microstructural changes have now been further examined with TEM. Even after recrystallization, proeutectoid α was found to faceted. Rational lattice orientation relationships were demonstrated between eutectoid α and Ti_2Ni and also between recrystallized α and Ti_2Ni. Interphase boundaries between eutectoid α and eutectoid Ti_2Ni, eutectoid α and β and eutectoid Ti_2Ni and β were shown to be ledged. Repeated interruption of Ti_2Ni lamellae by eutectoid α and observation of a somewhat larger ratio of ledge height to inter-ledge spacing on eutectoid α than on eutectoid Ti_2Ni indicate, on the considerations of an accompanying theoretical paper, that the eutectoid structure produced after thermomechanical processing is bainite. However, the drastic compaction of proeutectoid α morphologies engendered by the processing procedure permitted bainite to develop as nodules instead of the usual "plating out" of the bainitic $\alpha + Ti_2Ni$ structure on previously formed proeutectoid α plates and allotriomorphs.

2.6 Surface Relief Effects Associated with Proeutectoid Alpha Plates in a Ti-7.15 w/o Cr Alloy

(This paper is reproduced in Appendix V. It is being submitted to Acta Metallurgica.)

Surface relief effects associated with "normal α" and the "black plates" formed during the proeutectoid α reaction in a Ti-7.15 w/o (6.62 a/o) Cr alloy have been investigated. Approximately 80% of the reliefs examined were tent-shaped; the remainder were of the invariant plane strain (IPS) type. Both types of proeutectoid α

plate yielded similar tilt angles for a given type of relief effect. Whereas the tilt angle per side was c. 2-2 $1/2^\circ \pm 1^\circ$ for tent reliefs, it was c. $6^\circ \pm 2^\circ$ for those of the IPS type. TEM examination of plates in contact with the free surface demonstrated that all plates were laterally monocrystals; hence the tent-shaped reliefs could not have been caused by two plates formed back-to-back. TEM also showed that proeutectoid α plates contain no twins, whereas martensite plates formed in a comparable Ti-Cr alloy do, according to Ericksen, Taggart and Polonis. All plates studied formed above the T_o temperature Implications of these observations and related information, previously published, with respect to whether growth takes place by a shear or a diffusional mechanism are then considered in detail.

3. CRYSTALLOGRAPHY AND INTERFACIAL STRUCTURE OF GRAIN BOUNDARY ALPHA ALLOTRIOMORPHS IN A Ti-7.15 W/O Cr ALLOY

3.1 Introduction

This investigation constitutes the Ph.D. research of Mr. Tadashi Furuhara. Important contributions to this section of the report have been made by Miss Amber Dalley. Mr. Furuhara is taking his Ph.D. Qualifying Examination as this report is being written. Assuming a successful outcome, the pace of research on this topic should accelerate markedly in the near future.

The primary goals of this program are: (i) to examine the crystallography and interphase boundary structure of grain boundary allotriomorphs of proeutectoid alpha in hypoeutectoid Ti-Cr alloys with respect to both beta grains at whose interface the allotriomorphs formed; and (ii) to study the crystallography and interphase boundary structure of $TiCr_2$ crystals formed (during the bainite reaction) at both faces of grain boundary alpha allotriomorphs. Elementary nucleation theory (3) and a general theory of precipitate morphology (4) predict, contrary to much current wisdom, that all orientation relationships found during this investigation will permit the development of low energy interphase boundaries, and that these boundaries will be of the partially coherent type, capable of migration only through the agency of the ledge mechanism.

Low energy orientation relationships between grain boundary allotriomorphs and one of the matrix grains forming the grain boundaries at which they nucleate are now generally accepted. A current paper by Park and Ardell [5] confirms this view with particular thoroughness. Only limited evidence, on the proeutectoid ferrite reaction in steel [6] and on the $\beta \rightarrow \zeta_m$ massive transformation in a Ag-26 A/O Al alloy [7], in support of the idea that a low energy orientation relationships subsists with respect to the "other" matrix grain is now available. The main backing for this idea arose from the theoretical analysis of the experimental data obtained on the nucleation kinetics of grain boundary ferrite allotriomorphs at austenite grain boundaries in Fe-C alloys by Lange et al [8]. Further, the present investigation represents the first serious effort to examine in detail the interphase boundary structure of grain boundary allotriomorphs at either interphase boundary. That such a study has not been previously undertaken is not surprising. Unlike the broad faces of Widmanstatten plates, upon which much TEM effort has been lavished during the past 20 years [9], the interphase boundaries of allotriomorphs exhibit frequent changes in boundary orientation. Each such change ought to correspond to some alterations in interphase boundary structure. Hence the area in which a particular interfacial structure is present in constant fashion must be quite limited. Since the interphase boundary structures experimentally observed have usually not achieved their equilibrium configuration [4, 9], these structures are to some extent idiosyncratic. Assessment of their average character thus requires that the interfacial area at which a particular structure obtains be large enough--say at least 10-20 times greater than the largest spacing between parallel misfit dislocations--so that its essential average characteristics may be correctly apprehended. Since one might intuitively anticipate that the interphase boundaries of grain boundary allotriomorphs might not meet these specifications over their entire area, particularly during the early stages of growth, it is understandable that they have not proved to be an inviting initial target for research on interphase boundary structure.

However, extensive measurements have been made on the growth kinetics of grain boundary allotriomorphs developed during the proeutectoid ferrite reaction in Fe-C and Fe-C-X alloys [10-13]. Similar studies have recently been made with the support of this Grant on a Ti-Co alloy and on the present Ti-Cr alloy [14]. Correct interpretation of these measurements requires more information on the operative interphase boundary structure, and thus on the growth mechanism of allotriomorphs than is presently available. Hence the present investigation! Inasmuch as allotriomorphs are the first morphology to form at most grain boundaries, and hence the first morphology to develop in most polycrystalline alloys during diffusional phase transformations, the practical value of understanding the interfacial structure and growth mechanisms of allotriomorphs better than we do now should be obvious.

3.2 Experimental Aspects

The central experimental component of this program is again the drastic reduction in beta grain size achievable by rapid solidification. Grain growth in beta Ti alloys is so very rapid that the usual solution annealing treatment in the beta region produces only very coarse grain sizes, irrespective of the initial microstructure. However, research in Dr. Froes' group has demonstrated that very fine (less than 100 nm) beta grain sizes can be secured by means of rapid solidification.

As reported last year, we had rapid solidification experiments conducted on our Ti-Cr alloy at Wright-Patterson, Oak Ridge National Laboratory and IBM Thomas J. Watson Research Center, as part of Miss Dalley's research on the influence of beta grain size upon the formation of Widmanstatten alpha sideplates in Ti-Cr alloys. The Oak Ridge specimens, produced by the hammer-and-anvil technique, provided the most useful combination of grain size reduction with relatively small pick-up of interstitial impurities. Hence all of our experiments since then have been carried out on the Oak Ridge specimens.

In the case of the present program, fine beta grain sizes (of the order of a few microns in diameter) are needed for a more mundane but no less important reason. Unless the beta grain size is reduced to this level, the probability of finding a single beta grain boundary in the electron transparent area of a thin foil becomes so small that sample preparation for TEM becomes a very tedious and drawn-out affair. However, when rapidly solidified specimens are employed, each thin foil customarily contains several grain boundaries as illustrated in Figure 1. Hence the research can be markedly expedited.

Specimens are encapsulated in vacuo in a Vycor tube after wrapping in tantalum foil. Capsules are repeatedly lightly torched during successive evacuations to drive off adsorbed gases; they are flushed each time with dried and purified helium, and finally sealed off under vacuum.

During heat treatment, the encapsulated specimens are upquenched in a lead bath directly to the intended isothermal reaction temperature. Omega phase crystals present in the specimens should dissolve during the heating process, leaving a "pure" beta matrix from which grain boundary allotriomorphs can precipitate.

3.3 Results and Discussion

The qualitative observations to be presented are representative of many made by Mr. Furuhara and Miss Dalley. The quantitative determinations of orientation relationships, on the other hand, represent their initial effort of this type. Taken together, these results demonstrate that this program is feasible and that its outcome is likely to be that anticipated: all interfaces of grain boundary alpha allotriomorphs exhibit a ledge structure and should thus be partially coherent....and grow solely by means of the ledge mechanism. Thus, Fig. 2 shows conspicuous ledges on both sides of an allotriomorph. While these ledges are obvious only at certain boundary orientations, traces of ledges can be discerned elsewhere along these interphase boundaries. A higher magnification view of ledges is displayed in Fig. 3. The ratio of the inter-ledge spacing to the ledge height is seen to be no more than several-to-one. Fig. 4 presents an alpha allotriomorph at which the ledge structure is more easily discerned at most orientations of the alpha:beta boundary enclosing this crystal. Higher resolution views of a portion of this boundary are presented in dark field and bright field, respectively, in Fig. 5. It seems possible--but not certain, pending a more quantitative analysis--that two systems of growth ledges are simultaneously operative at this boundary. In Fig. 6, a lower magnification view of the allotriomorph shown in Figs. 4 and 5 is reproduced, together with selected area electron diffration patterns taken astride the allotriomorph and the "upper", and the allotriomorph and the "lower" beta grain, respectively. A Burgers orientation relationship is seen to obtain between the allotriomorph and the lower beta grain, consistently with the more pronouncedly faceted boundary separating the latter crystals. Faceting is less apparent along the "upper" boundary and the orientation relationship--as yet incompletely deciphered--seems highly irrational. Yet Fig. 4 indicates that this boundary is also of the low energy, i.e., faceted and ledged type.

3.4 Future Plans

Having established the feasibility of this investigation, we now plan to characterize quantitively the interphase boundaries on both sides of a number of grain boundary alpha allotriomorphs, formed at progressively larger undercoolings below the transus. Efforts will be made to effect these characterizations at allotriomorphs precipitated at beta grain boundaries formed by a wide range of misorientations. Characterization of a given alpha:beta boundary will include:

(i) lattice orientation relationship across the boundary;

(ii) habit planes in both phases comprising planar facets on the boundary;

(iii) measurement of average inter-ledge spacing and average ledge height at individual planar facets;

(iv) determination of the habit planes of the terraces, and if possible, of the risers of the ledges (the latter is likely to be only rarely feasible);

(v) quantitative characterization of the misfit dislocation structure expected on terraces of the ledges, including delineation of the idealized pattern of the misfit dislocations, determination of the Burgers vector of the dislocations, of the angle between the Burgers vector and the terrace plane and an estimation of the proportions of edge and of screw components of the misfit dislocations in a given array.

O-lattice analysis [15] will then be employed in order to ascertain whether or not the observed dislocation structures approximate to those anticipated at equilibrium.

In collaboration with Dr. Masato Enomoto, Tsukuba Laboratories, National Research Institute for Metals, Japan, who has made a finite element analysis of the growth kinetics of closely spaced, i.e., diffusionally interacting ledges [16], the inter-ledge spacing data to be secured as a function of isothermal reaction temperature during the present investigation will be combined with the growth kinetics data on grain boundary alpha allotriomorphs in the present alloy previously reported by Menon and Aaronson [14] to re-evaluate the growth mechanism of the allotriomorphs. Assuming that the allotriomorphs have a predominantly disordered interfacial structure, Menon and Aaronson concluded that their growth kinetics are somewhat too rapid for control of growth by volume diffusion of Cr directly away from the allotriomorphs. They therefore suggested that the "rejector plate mechanism"--a solute-poor precipitate's counterpart to the "collector plate mechanism" [17]--accelerates growth of the allotriomorphs by preferential diffusion of Cr along the alpha:beta boundaries and thence along the beta grain boundaries. Only if the growth kinetics of the allotriomorphs as calculated from the measured inter-ledge spacings and the Enomoto analysis remain more rapid than those experimentally determined will the rejector plate mechanism still be considered to be operative.

We also plan to use SEM to examine the surface relief effects associated with grain boundary alpha allotriomorphs. This morphology has been generally agreed not to produce such reliefs at a free surface [18] because its interphase boundaries have ben considered to be predominantly disordered [19, 20]. Because the terraces whose displacements generate the reliefs are both short and probably also short-lived as a result of diffusional interactions between adjacent ledges, it seems likely that the invariant plane strain or tent-shaped reliefs which we predict are associated with the growth of a grain boundary allotriomorph should develop only on a very fine scale. But now that we expect to find such reliefs, we should be able to ascertain whether or not they actually exist by means of either SEM or some form of TEM. If the presence of these reliefs can be reliably established, as a general characteristic of grain boundary allotriomorphs, then important further evidence will be at hand in support of our view that the observation of martensite-type surface reliefs does not constitute sufficient proof that the growth mechanism of a phase transformation is shear [4, 21].

4. MASSIVE TRANSFORMATION

4.1 The $\beta \rightarrow \zeta_m$ Massive Transformation in a Ag-26 A/O Al Alloy

This will be the Ph.D. thesis research of Mr. Yiwen Mou. He will begin his experiments during the summer of 1987, after he has completed a graduate course in TEM. His objective will be to characterize the crystallography and structure of massive:matrix boundaries in this alloy--previously used for orientation relationships studies performed with the support of this Grant [7]--in just the manner described for grain boundary allotriomorphs. The objective of the investigation is to test our view [22, 23] that low energy lattice orientation relationships and partially coherent interphase boundaries displaced by means of the ledge mechanism are just as prevalent during the massive transformation as they are during precipitation from solid solution, despite long-held and generally accepted views to the contrary [24]. The basis for our view is that nucleation theory is equally applicable to both types of transformation. The requirement that nucleation is unlikely to be detectable unless the activation free energy for critical nucleus formation is less than 30-60kT [25] can normally be met, particularly at low undercoolings below the T_o temperature, only when low energy interfaces bound critical nuclei [23, 26].

4.2 Aspects of the Massive Transformation

In collaboration with former graduate students Dr. Sarath Menon and Prof. Mark Plichta, a number of important aspects of the massive transformation have been reconsidered. The paper prepared upon the basis of this effort is reproduced in Appendix VI. Its abstract is presented in the following paragraph as a summary of the essential features of this study.

Re-analysis of published growth kinetics data for the massive transformation in six different alloy systems indicates that growth by the ledge mechanism is a reasonable possibility in all of them. Variations in the ratio of the inter-ledge spacing to the ledge height with boundary orientation and in the temperature-dependence of growth kinetics with boundary orientation also seem likely. Plateaux in plots of thermal arrest temperature vs. a function of cooling rate are suggested to arise from changes in massive morphology with decreasing transformation temperature, derived from variations with boundary orientation of temperature-dependent growth kinetics. Solute "burial" during the massive transformation is concluded usually to be feasible only when the driving force for transfer back to the matrix of the atoms undergoing burial is much less than that for solvent atoms diffusing from the matrix to the product phase. Invariant plane strain surface reliefs can be generated during massive transformations when reaction occurs at sufficiently large undercoolings so that markedly anisotropic growth, involving comparatively large areas of partially coherent interphase boundary with a constant boundary orientation, is feasible. Massive transformation in a two-phase field below T_o is probably viable when the volume diffusivity in the matrix is too low relative to the trans-interphase boundary diffusivity to permit appreciable solute partition during growth.

5. INTERACTION WITH STRUCTURAL MATERIALS BRANCH, MATERIALS LABORATORY, WRIGHT-PATTERSON AFB

As a result of the busy schedule of the P.I. and the even busier one of Dr. F. H. Froes, the P.I.'s host at Wright-Patterson, only two visits to Dr. Froes' Group were made during the past year. However, the next visit will be made before this report is received: January 23, 1987. These visits continue to be enjoyable and Dr. Froes schedules very full days for the P.I. During both visits, seminar talks were given on the main results of Dr. E. S. K. Menon's Ph.D. Thesis on the proeutectoid alpha reaction in Ti-X alloys; this investigation was carried out entirely with the support of the present Grant.

Collaboration continues on research dealing with the influence of beta grain size upon the formation of the Widmanstatten morphologies of the proeutectoid alpha reaction, and on growth ledges on Widmanstatten sideplates. Both of these investigations are being conducted on Ti-6% Al-4% V in collaboration with Dr. Froes and Dr. D. Eylon. The latter investigator, formerly with Wright-Patterson AFB but now an associate professor at the University of Dayton, has been much occupied with first-year tasks in his new position. Hence progress in these studies has been slower than would have been desired; however, we hope that both investigations can soon be brought to a conclusion.

A wide range of subjects is considered with Materials Laboratory staff members during a typical visit. For example, during the visit paid on ept. 12, 1986, topics discussed with WPAFB colleagues included: high strength Al-base alloys and the role of grain boundary precipitation in their embrittlement, ductility of $AL_{10}V$, strengthening of Ti_3Al by rare earth oxides introduced during rapid solidification, grain boundary embrittlement problems encountered in Al_3Ti, thermomechanical processing of Ti-10% Nb alloys (containing small proportions of V, Mo and Al) and their embrittlement by what appears to be a cellular reaction, mechanisms of eutectoid decomposition in rapidly solidified Ti-Ni alloys, high-temperature aluminum and titanium alloys and also cermets involving TiC, deformation of Ti_3Al (with 30% Nb added to stabilize the CsCl structure) and the creep and oxidation resistance of Ti-Al-Sn-Zr-Mo alloys. A detailed report letter is written after each visit to summarize for Dr. Froes the topics discussed and to permit the supply of further information and ideas about these topics which developed afte: the visit.

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FIGURE CAPTIONS

Figure 1. Bright field TEM micrograph of proeutectoid alpha grain boundary allotriomorphs in retained β matrix in Ti-7.22 w/o Cr reacted for 20 min at 750°C.

Figure 2. Bright field micrograph showing the change in ledge height and spacing at both matrix:allotriomorph interphase boundaries as boundary orientation varies in Ti-7.22 w/o Cr reacted at 750°C for 20 min.

Figure 3. Dark field micrograph of superledges at one allotriomorph:beta matrix interphase boundary in Ti-7.22 w/o Cr reacted for 30 min. at 750°C.

Figure 4. Another example of ledge structure along an allotriomorph matrix interphase boundary shown by a bright field TEM micrograph in Ti-7.22 w/o Cr reacted at 750°C for 20 min.

Figure 5. High magnification bright field (a) and dark field (b) images of the ledged lower boundary shown in Fig. 4.

Figure 6 A non-Burgers orientation relationship is shown by the SAD pattern (a) and schematic (b) between the grain boundary allotriomorph and upper β grain (c). The allotriomorph is Burgers-related to the lower grain where the $[111]_\beta$ zone axis is parallel to the $[11\bar{2}0]_\alpha$ direction as shown in SAD pattern (d), and schematic (e). The allotriomorph is the same as that shown in Fig. 4.

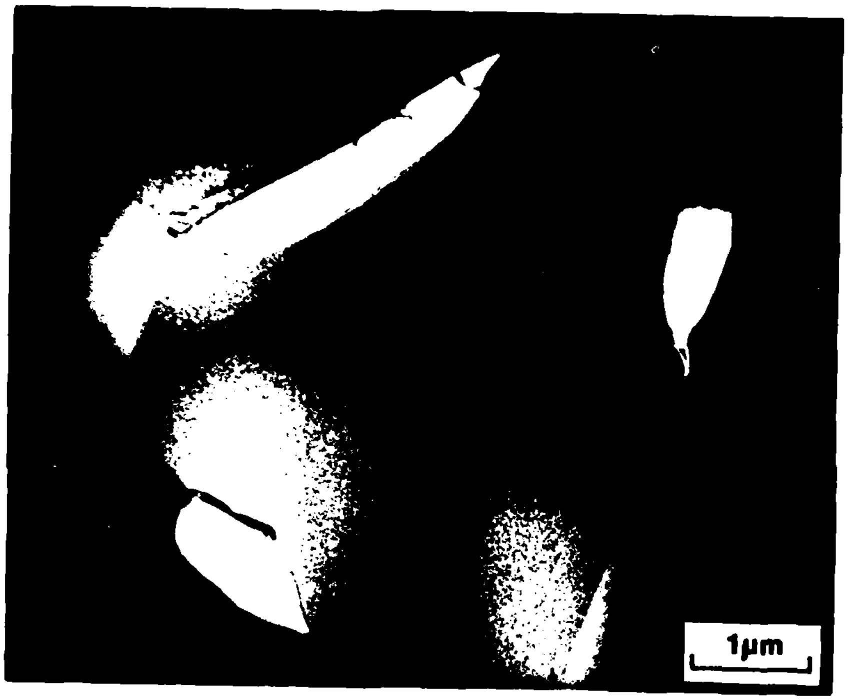

Figure 1

Figure 2

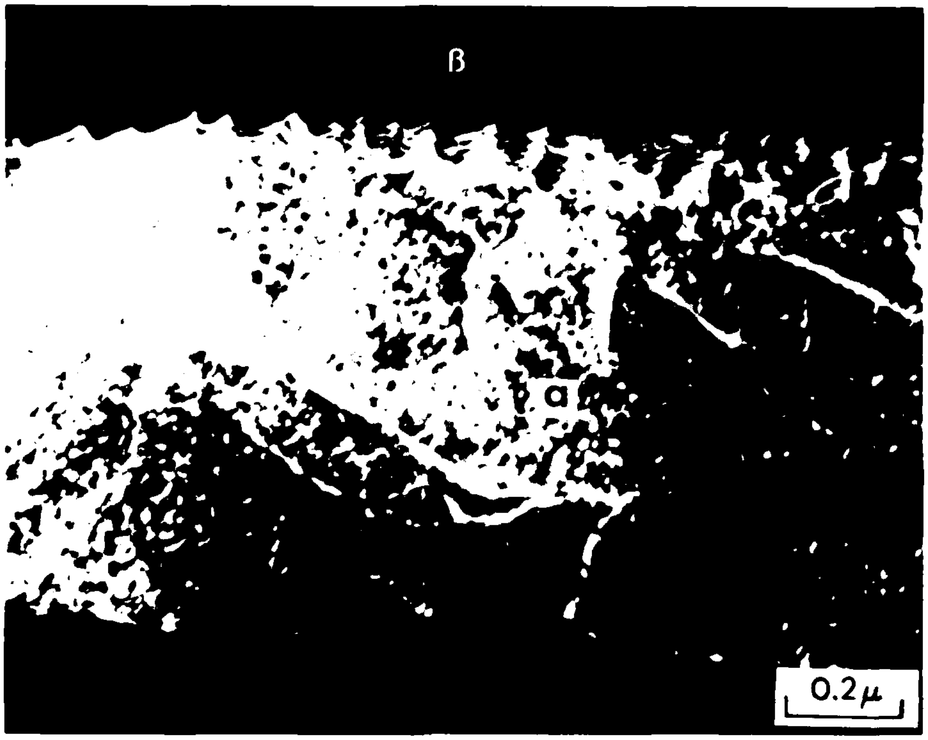

Figure 3

Figure 4

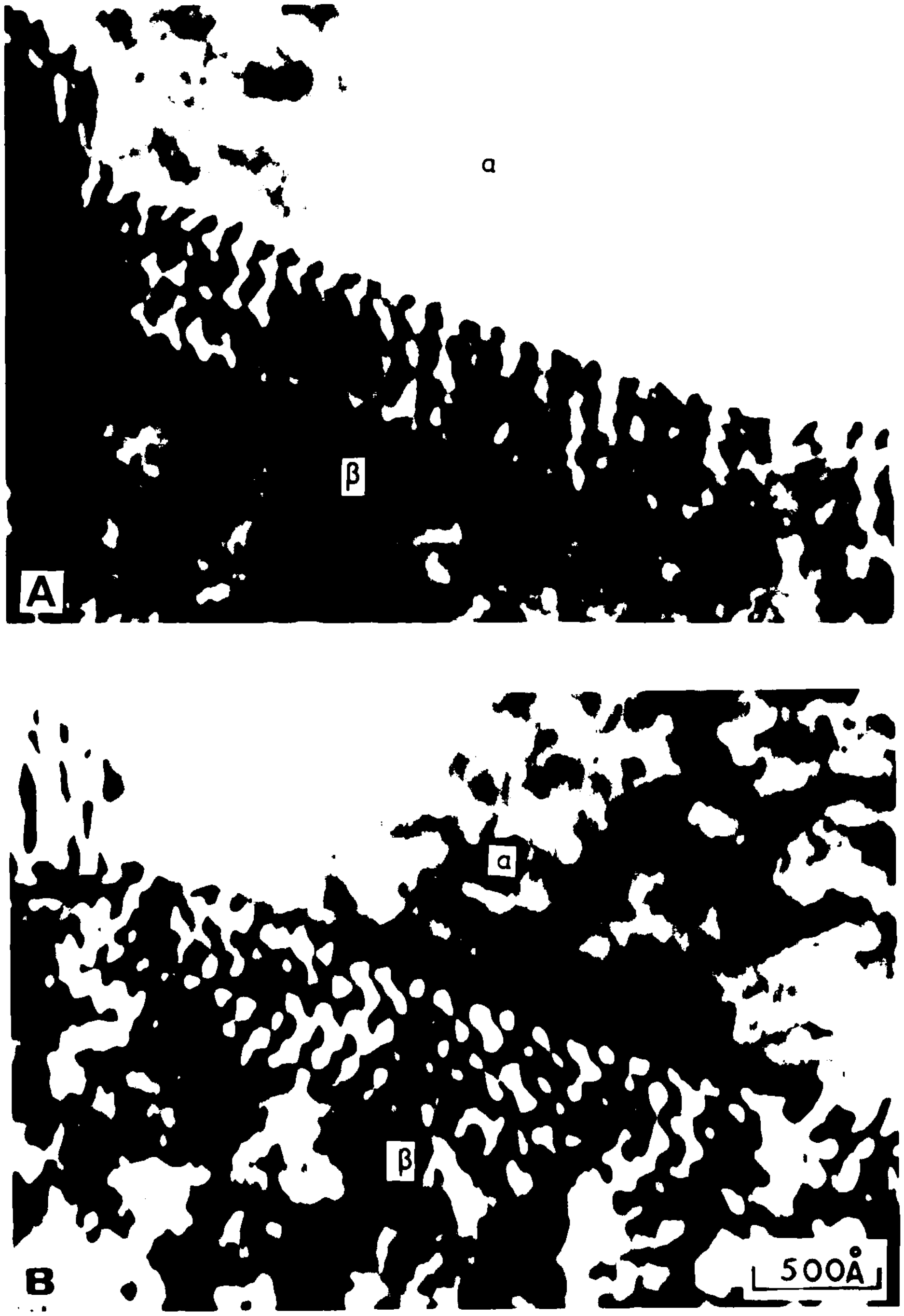

Figure 5

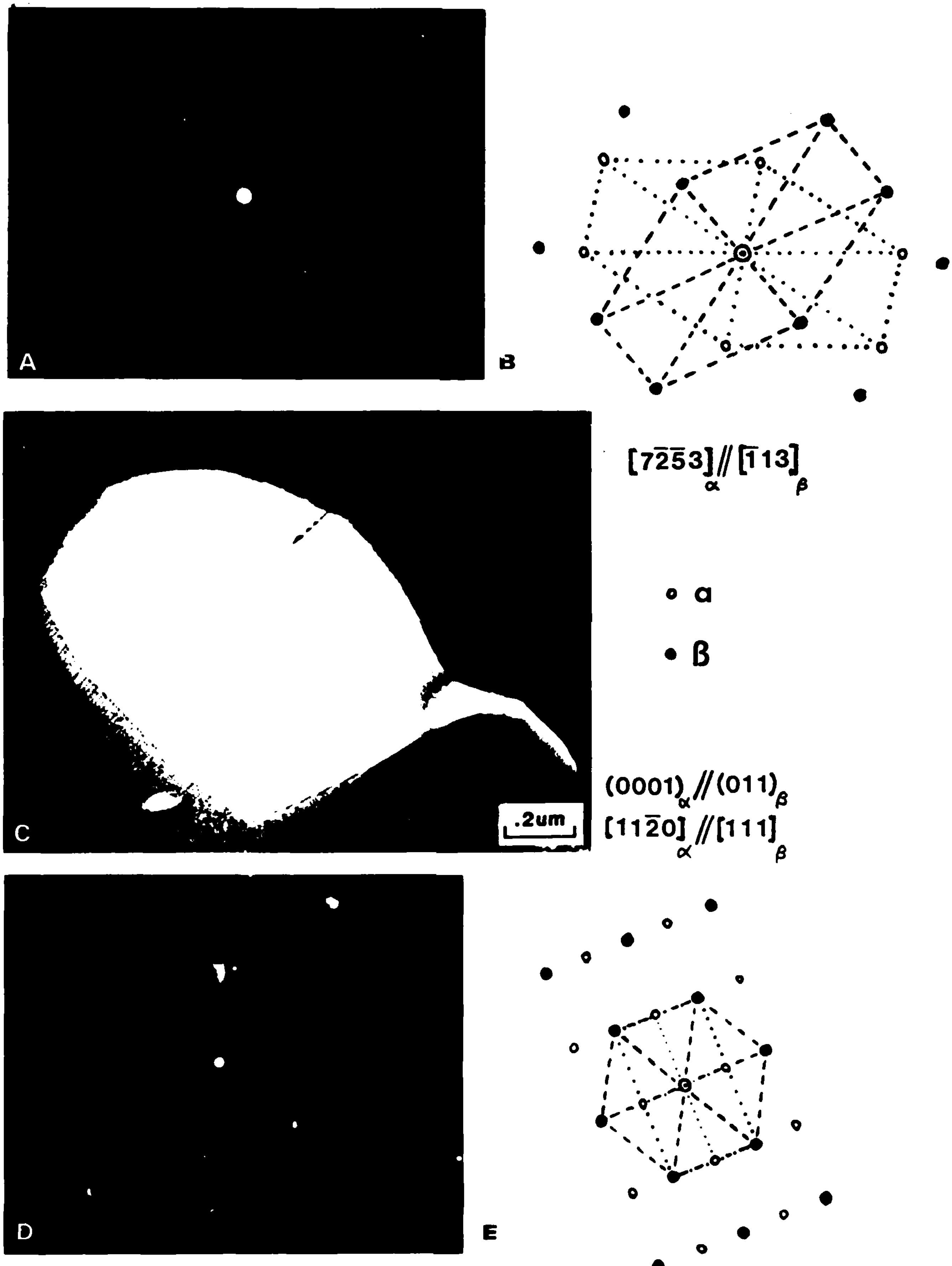
A
B
C
D
E
$[7\bar{2}\bar{5}3]_{\alpha} // [\bar{1}13]_{\beta}$
∘ α
• β
.2um
$(0001)_{\alpha} // (011)_{\beta}$
$[11\bar{2}0]_{\alpha} // [111]_{\beta}$

Figure 6

END

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