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**TRANSFORMATION RATES
OF
PLASTICALLY DEFORMED PLUTONIUM**

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ABSTRACT

Plastic deformation of the stable beta phase in plutonium retards the $\beta \rightarrow \alpha$ transformation. This is consistent with known martensitic transformations. There are insufficient dislocations in plastically deformed alpha to retard $\alpha \rightarrow \beta$ transformation, but sufficient dislocations are present to accelerate it. Deformed alpha plutonium can be annealed at 105 °C.

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By

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February, 1966

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INTRODUCTION

The effect of plastic deformation of the stable parent phase on the kinetics of the subsequent $\beta \rightarrow \alpha$ and $\alpha \rightarrow \beta$ transformations in plutonium was studied to provide information on the mechanics of these transformations. The results are discussed, and they are compared to results from similar experiments on other metals and alloys.

The parent phase of a martensitic transformation will be stabilized by significant amounts of plastic deformation. Plastic deformation of the stable parent phase may either depress the M_s temperature or slow the isothermal transformation rate, whichever is applicable. This inhibiting effect of plastic deformation, the lowering of transformation rates, is referred to as mechanical stabilization, and has been observed in iron alloys⁽¹⁻⁷⁾. Plastic deformation of the parent phase is known to decrease the rates of martensitic transformations in the systems, cerium⁽⁷⁾ and cobalt⁽⁸⁾, as well as the iron alloys. The reduction of transformation rates of the stable parent phase has not been observed in diffusional transformations. On the contrary, plastic deformation always accelerates diffusional transformations because it promotes nucleation and growth⁽⁹⁾.

The effect of plastic deformation of a stable parent phase on transformation rates is to be differentiated from the effect of plastic deformation of an unstable parent phase. The transformation rate is accelerated by plastic deformation of the unstable parent phase for both martensitic and diffusion controlled transformations⁽¹⁰⁻¹²⁾; the extent of the effect depends upon the sluggishness of the transformation.

Fiedler, Averbach, and Cohen⁽¹⁾ found that plastic strains up to 2% elongation in the stable parent phase favored the

austenite $\rightarrow$ martensite transformation, but plastic strains above 2% elongation hindered the subsequent transformation. They suggested that mechanical stabilization of this alloy was due to the distorted structure of the deformed austenite; the high dislocation density and deformed lattice of the cold-worked austenite interferes with the propagation of martensite, but residual stresses may assist nucleation. Kurdjumov^(13,14) observed similar mechanical stabilization in a steel containing 0.954% C and 3.5% Mn.

Thus, the effects of plastic deformation of the parent beta and alpha phases on the $\beta \rightarrow \alpha$ and $\alpha \rightarrow \beta$ transformations were determined to see whether the results are consistent with known martensitic transformations.

INFLUENCE OF BETA PLASTIC DEFORMATION ON THE $\beta \rightarrow \alpha$ TRANSFORMATION KINETICS

The influence of the plastic deformation of beta plutonium on a subsequent transformation to the alpha phase was investigated. A series of specimens from the same melt were transformed from alpha to beta at 160 °C and then compressed in the range 0 to 95% reduction in thickness at 140 °C and 150 °C. The beta phase formed from alpha is hereafter designated β_α . The specimens were allowed to transform to the alpha phase at 80 °C. This transformation temperature yielded reasonable times for the start of the $\beta_\alpha \rightarrow \alpha$ transformation in specimens that were or were not plastically deformed.

Typical $\beta_\alpha \rightarrow \alpha$ isothermal reaction curves of undeformed and deformed metal are given in Figure 1. Density measurements at 80 °C permitted the isothermal reaction process to be followed. The data shows that beta plastic deformation increases the $\beta_\alpha \rightarrow \alpha$ incubation time and decreases the $\beta_\alpha \rightarrow \alpha$ transformation rate. Plastic deformation of β_α at 140 °C followed by transformation to alpha at 80 °C produced alpha metal having a very nonrandom

Time, Seconds
FIGURE 1

Effect of Beta Plastic Deformation on the Plutonium $\beta_{\alpha} \rightarrow \alpha$ Transformation at 80 °C

grain structure. The metal consists of bands of columnar grains as shown in Figure 2 (Note extensive banding caused by the plastic formation polarized light). Banding in deformed specimens is much greater than in undeformed specimens with similar thermal treatments.

Similar experiments were performed on beta phase plutonium that had been formed from gamma, hereafter designated β_γ . Plastic deformation of β_γ increased the time for start of the $\beta_\gamma \rightarrow \alpha$ transformation. Plastic deformation of β_γ also markedly decreased the $\beta_\gamma \rightarrow \alpha$ transformation rate. Because the $\beta_\gamma \rightarrow \alpha$ transformation rate is greater than the $\beta_\alpha \rightarrow \alpha$ transformation rate, β_γ specimens were transformed to alpha at temperatures higher than 80 °C to yield approximately equal transformation rates for the undeformed beta phase. The maximum $\beta_\gamma \rightarrow \alpha$ transformation rate and incubation time at 90 °C equalled the maximum $\beta_\alpha \rightarrow \alpha$ transformation rate and incubation time.

The study of the effect of deformation temperature on the $\beta_\gamma \rightarrow \alpha$ and $\beta_\alpha \rightarrow \alpha$ transformations in specimens reduced 75 to 85% in thickness by compression showed that increased deformation temperatures resulted in slower transformation rates for both the $\beta_\alpha \rightarrow \alpha$ and $\beta_\gamma \rightarrow \alpha$ (Figure 3). Apparently, a critical amount of beta deformation is needed to decrease the $\beta \rightarrow \alpha$ transformation rate. As shown in Figure 4, this critical amount is about 10% for deformation by compression at 150 °C. For deformation beyond this amount, the transformation rate decreases with increasing prior deformation.

Because the rates of diffusion controlled transformations are normally increased, rather than decreased, by plastic deformation, it is inferred that diffusion of individual atoms is not a major part of the $\beta \rightarrow \alpha$ transformation because plastic deformation retards the $\beta \rightarrow \alpha$ transformation. The observed effects of plastic deformation appear to parallel those for which the concept

FIGURE 2

Microstructure of Plutonium Plastically Deformed
(60% by Compression) in the Beta Phase and then
Isothermally Transferred at 80 °C

FIGURE 3
Effect of Beta Deformation Temperature
on the Plutonium $\beta_{\alpha} \rightarrow \alpha$ and
 $\beta_{\gamma} \rightarrow \alpha$ Transformation Rates

FIGURE 4

Effect of Beta Plastic Deformation at 150 °C
on the $\beta_{\alpha} \rightarrow \alpha$ Transformation Rate at 80 °C

of mechanical stabilization of parent phases in martensitic transformations apply.

INFLUENCE OF ALPHA PLASTIC DEFORMATION ON THE $\alpha \rightarrow \beta$ TRANSFORMATION KINETICS

Plastic deformation of the stable parent alpha phase accelerated the $\alpha \rightarrow \beta$ transformation at slow transformation rates. Specimens were compressed about 40% in thickness at $80^\circ \pm 10^\circ \text{C}$. The representative $\alpha \rightarrow \beta$ isothermal reaction curves (Figure 5) clearly show the accelerating effect of the $\alpha \rightarrow \beta$ transformation rate by plastic deformation of the alpha phase material. The effects of the temperature of deformation and the amount of deformation on the $\alpha \rightarrow \beta$ transformation rate were not investigated.

Specimens of alpha that had been deformed by compression were annealed at 105°C to determine whether cold work could be annealed out of alpha plutonium. The $\alpha \rightarrow \beta$ transformation rate was used as an indirect measure of annealing since deformation accelerates the $\alpha \rightarrow \beta$ transformation rate. If annealing reduces the degree of cold work, it should also decrease the $\alpha \rightarrow \beta$ transformation rate. Seven specimens were compressed to one-half their initial thickness at 60°C . They were then annealed for different times at 105°C . The results showed that deformed alpha plutonium does anneal at 105°C , as indicated by the time for start of transformation and by the $\alpha \rightarrow \beta$ transformation rate (Table I). About two weeks annealing time is required to regain the initial values for the undeformed alpha. These results imply that the deformation remaining in plutonium after compression is only in the form of residual stresses, which accelerate the $\alpha \rightarrow \beta$ transformation.

CONCLUSIONS

Deformation of the stable parent phase results in a reduced transformation rate in phase changes that are martensitic. Results on Fe-Cr-Ni alloys substantiate this statement^(1-6, 13, 14). Russian investigators⁽¹²⁾ used this inhibiting effect as a

FIGURE 5
Effect of Alpha Plastic Deformation on the
Plutonium $\alpha \rightarrow \beta$ Transformation at 118°C

TABLE I

ANNEALING OF DEFORMED α -PLUTONIUM AS REVEALED
BY THE INCUBATION TIME* AND THE TIME FOR
50% TRANSFORMATION OF THE $\alpha \rightarrow \beta$ TRANSFORMATION

<u>Annealing Time</u> <u>at 105 °C hr</u>	<u>Times Required for $\alpha \rightarrow \beta$</u> <u>Transformation at 119 °C</u>	
	<u>Incubation</u> <u>Time</u>	<u>Time for 50%</u> <u>Transformation</u>
0	350	2240
1	1300	4000
2	2000	7200
4	3000	9500
24	3500	9800
120	5300	12 000
700	5500	12300

criterion for a martensitic transformation, because such an inhibiting effect of plastic deformation of the stable parent phase has been observed only for martensitic transformations and has not been observed for diffusional transformations. Plastic deformation always accelerates diffusional transformations⁽⁹⁾ since it promotes both nucleation and growth. Accordingly, the plutonium $\beta \rightarrow \alpha$ transformation is martensitic because plastic deformation of the stable beta phase retards the $\beta \rightarrow \alpha$ transformation.

The accelerating effect of plastic deformation of the stable alpha phase on the plutonium $\alpha \rightarrow \beta$ kinetics is not in itself a sufficient criterion for categorizing this transformation. Although plastic deformation always accelerates diffusional transformations, small amounts of plastic deformation may accelerate martensitic transformations as well. Thus, acceleration of a transformation by plastic deformation is consistent with either diffusional or martensitic transformations. Since alpha plutonium does not strain harden easily⁽¹⁵⁾, it can be reasoned that an insufficient number of dislocations is introduced by plastic deformation to block the $\alpha \rightarrow \beta$ transformation if it is martensitic. The number of dislocations introduced is sufficient to accelerate nucleation, even though the transformation may be martensitic.

According to the evidence of this report, the influence of plastic deformation of the stable, parent beta phase prior to the $\alpha \rightarrow \beta$ and $\beta \rightarrow \alpha$ phase changes in plutonium on the kinetics is consistent with other martensitic transformations. However, the $\alpha \rightarrow \beta$ transformation may be either diffusional or martensitic, but the $\beta \rightarrow \alpha$ transformation, which is retarded by plastic deformation, must definitely be a martensitic transformation.

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