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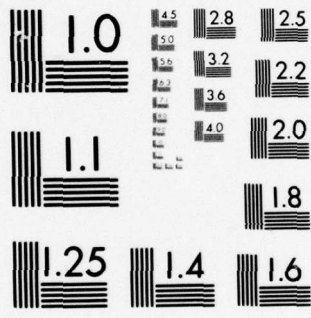
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On the Nature of the Anisotropy of the
Mechanical Properties of Hot-Rolled
Titanium Alloy Plate

Kazakevich, G. S.; O prirode anizotropii mekhanicheskikh svoystv goryachekatanykh listov iz titanovykh splavov; Transactions of M. I. Kalinin Leningrad Polytechnic Institute, No. 263; In: Mashiny i tehnologiya obrabotki metallov davleniyem. (Machines and Technology of Metal Working by Pressure.) Moscow, Leningrad, Mashinostroyeniye Publishing House, 1966, pp. 56-61.



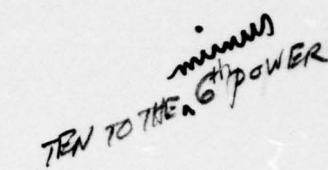
The present study was conducted subsequently to the publication of the preliminary results cited in reference [1] and is part of the work being carried out under the direction of Professor V. S. Smirnov, corresponding member of the Academy of Sciences of the USSR.

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Formerly, predominant crystallographic orientation in deformed metals with a hexagonal lattice were evaluated by the x-ray method, which is very labor intensive. Reference [2] suggests as an alternative the dilatometric method.

→ In this work use was made of the dilatometric method involving a mathematical statistical analysis of the change

→ over




 in the linear thermal expansion coefficient as a function of the orientation of specimens in 12 directions in the three main planes of plate No. 1, which had a striated macrostructure of the α -alloy Ti-Al after hot rolling and ordinary annealing. The anisotropy of the mechanical properties of this plate was cited in reference [1]. The coefficient $\alpha \cdot 10^{-6}$ was measured in six temperature intervals from 20-100 to 20-600°C on a differential dilatometer of the Cheveneau system with DR-49 type photo-recording. The measurements were made on two specimens for each orientation. The experiment results are summarized in the table below.

The following designations were adopted for the orientations of the specimens' longitudinal axis both in the table and elsewhere in the text; x is the direction over the plate's length; y is the direction over its width and z is the direction over the plate's thickness. The designations for the intermediate orientations in the planes xy, yz and zx also indicate the angle of incline of the specimen's axis to the first of the two axes which determine the given plane; for example, zx-30° indicates that the longitudinal axis of the speci-

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men in the plane zx forms a 30° angle with respect to the z -axis.

If \bar{x} is the arithmetic mean of the values ($\alpha \cdot 10^{-6}$) obtained in all 12 directions N (in the given temperature interval), then $\bar{\sigma}$ is the average quadratic deviation of the individual measurement x_i and is determined by the formula

$$\bar{\sigma} = \sqrt{\frac{\sum (\bar{x} - x_i)^2}{N}}.$$

When there is no predominant crystallographic orientation, the deviations of individual measurements of x_i from the mean \bar{x} should follow the normal law of distribution. In this case an error in the individual measurement of the value $\alpha \cdot 10^{-6}$, i.e. the difference between the arithmetic mean \bar{x} and the given value x_i , should not be greater than $3\bar{\sigma}$, as noted in reference [3]. As the table shows, this condition is met in all six temperature intervals.

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The table also shows the confidence intervals of the average value $\alpha \cdot 10^{-6}$ which were computed using the probability integral for a small sampling, as cited in

Table

Results of the statistical processing of the linear thermal expansion coefficient values of Ti-Al alloy plate metal for various specimen orientations

Temperature measurement interval, °C	Arithmetic mean \bar{x} of the values $\times 10^{-6}$	Deviation of points from the average values for the indicated orientation of the specimens' longitudinal axis in the system of the plate's main axes										\bar{y}	$3\bar{y}$	S_x	ϵ	Confidence intervals of the values $\times 10^{-6}$			
		x	xy = 30°	xy = 45°	xy = 60°	y	yx = 60°	yx = 45°	yx = 30°	zx = 30°	yz = 30°						yz = 45°	yz = 60°	z
20-100	8.7	0	0	+0.2	-0.1	-0.1	-0.1	-0.1	+0.5	-0.1	-0.1	-0.1	-0.1	+0.1	0.18	0.54	0.054	0.15	8.7±0.2
20-200	9.0	-0.1	-0.1	+0.2	-0.1	-0.1	-0.1	-0.2	+0.4	-0.2	-0.1	-0.1	-0.1	+0.1	0.17	0.51	0.051	0.14	9.0±0.1
20-300	9.2	0	0	+0.2	0	0	0	-0.2	+0.4	0	0	0	+0.1	0.14	0.42	0.042	0.11	9.2±0.1	
20-400	9.6	0	0	+0.2	0	0	0	-0.2	+0.2	0	-0.1	-0.1	0	0.11	0.33	0.033	0.09	9.6±0.1	
20-500	9.9	0	+0.1	+0.1	0	0	-0.3	+0.3	0	0	-0.1	-0.1	0	0.14	0.42	0.042	0.11	9.9±0.1	
20-600	10.2	0	+0.1	+0.1	-0.1	0	-0.3	+0.2	-0.1	-0.1	-0.1	-0.1	0	0.14	0.42	0.042	0.11	10.2±0.1	

reference [3]

$$P(t \pm t_\alpha) = 2 \int_0^{t_\alpha} S(t, k) dt,$$

where $K=N-1$.

This integral evaluates the probability that the deviation t from the sample¹⁷⁾ arithmetic mean \bar{x} will not exceed a certain number t_α ; one assumes the normal law of the distribution of deviations from the mean a . The largest values of t_α for various probability values and various k are tabulated in reference [3]. The calculation, therefore, can be performed rapidly.

The intermediate calculation parameters are indicated in the table by $S_{\bar{x}} = \frac{S}{\sqrt{N}}$, where

$$S = \sqrt{\frac{\sum(\bar{x} - x_i)^2}{N-1}}$$

is the corrected average quadratic deviation. With this correction the mathematical expectation $ES^2 = \sigma^2$; then the general mean a (the mathematical expectation of the value x_i) is determined by the confidence interval

$$a = \bar{x} \pm \xi,$$

where $\xi = t_\alpha S_{\bar{x}}$.

Assuming a fairly high probability $\alpha = 0.98$, one obtains the tabular value t_α for $k = 11$ ($N=12$).

The measurement data for the coefficient $\alpha \cdot 10^{-6}$ in 12 different directions, as well as the results of the processing of experimental data, thus, suggest that predominant crystallographic orientation does not develop in hot rolled titanium plate. This conclusion agrees completely with the preliminary conclusion stated in reference [1].

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It is possible, however, that an x-ray study of such plate may show asterism. But the reason for the latter would not be predominant crystallographic orientation, but rather lattice distortion, which always occurs in the vicinity of dislocation clusters, as noted in reference [4]. Plastic deformation is accompanied by the generation and movement of dislocations, and with irregular deformation there occur orientating dislocation clusters. During hot working by pressure, thermally activated movement of dislocations takes place, as noted in reference [4]. Alloying and impurity atoms actively affect this movement, but it is as yet impossible to account quantitatively for all the factors of this complex process as applied to technical alloys.

One can evaluate the influence of alloying and impurity elements on the anisotropy of hot rolled plate of the titanium alloys Ti-Al and Ti-Al-V on the basis

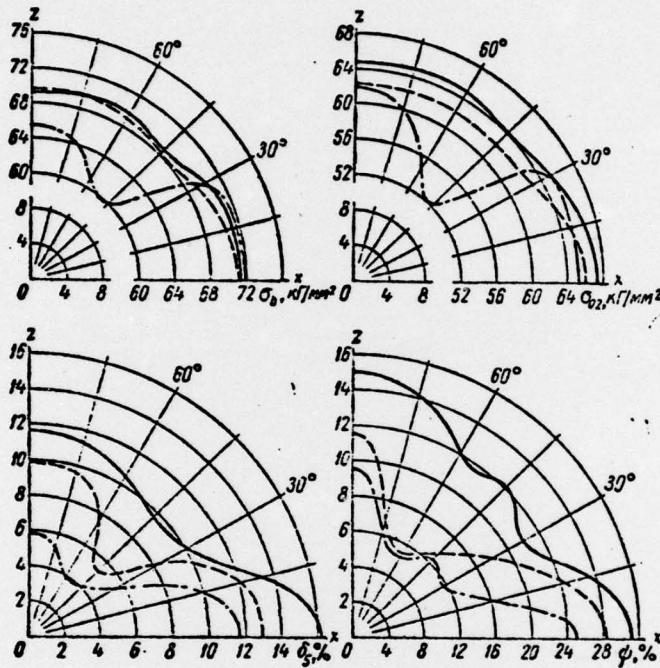


Fig. 1. The anisotropy of the mechanical properties of Ti-Al alloy plate for various oxygen impurity contents (plane xz): ———— 0.09%; - - - - 0.12%; - · - · - 0.19%

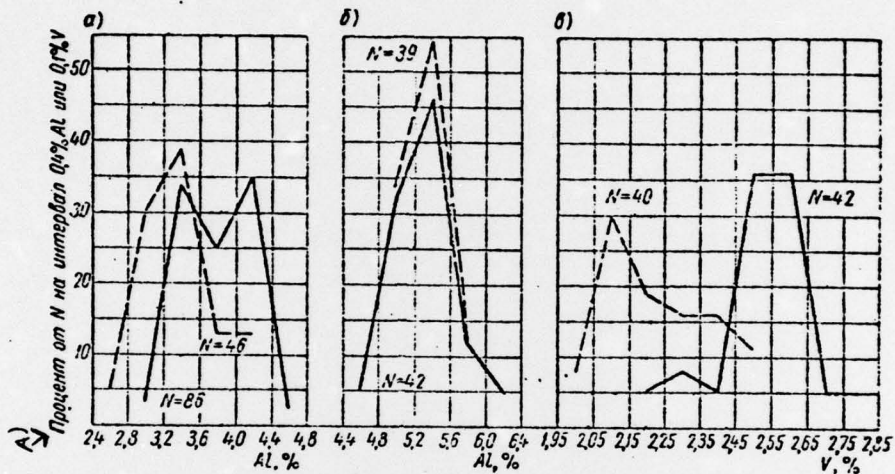
of Figs. 1, 2, and 3.

Fig. 1 shows that a plate of the α -alloy Ti-Al with a striated macrostructure after hot rolling and annealing, containing 0.09% oxygen impurity (here and subsequently the oxygen content was determined by vacuum melting), has the least anisotropy both of strength

properties (tensile strength σ_b and theoretical yield point $\sigma_{0.2}$ under tension) and plastic properties (relative elongation δ_5 and reduction in area ψ).

Circular specimens with an effective working area 5mm in diameter were subjected to tensile tests. In the metal with a 0.12% oxygen content the anisotropy of the strength properties does not change, but the anisotropy of the plastic properties increases significantly. Metal with 0.19% oxygen was found to be highly anisotropic both as to strength and plastic properties.

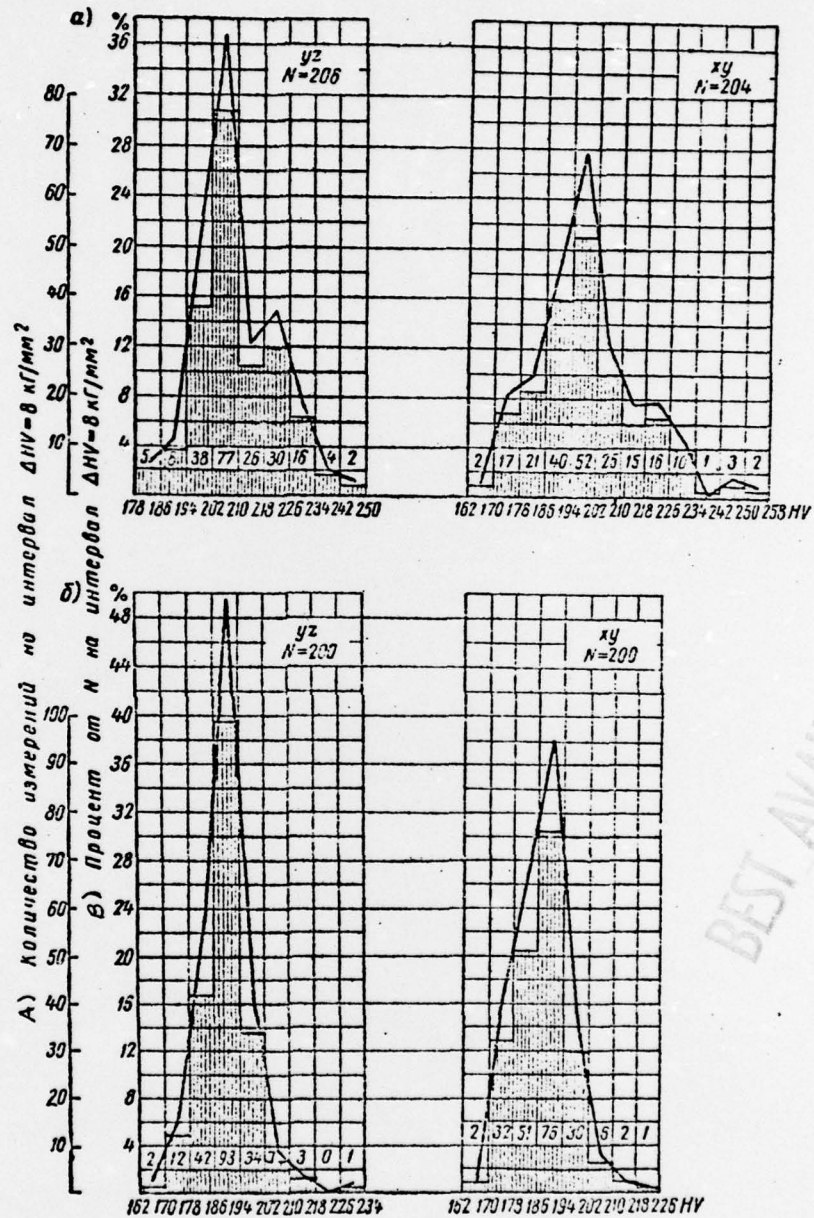
The hot rolling of titanium alloy plate ordinarily ends in the phase transition temperature region $\beta \rightarrow \alpha + \beta$. As the first low-temperature α -phase grains of titanium with a hexagonal densely packed crystal lattice are separated from the β -phase in the concluding stage of rolling, they tend to acquire a predominant crystallographic orientation (texture) and in accordance with the laws of the crystallization of solid solutions have been found to be oxygen enriched. Thus, there are created in the metal oriented areas of high oxygen concentration exceeding the average level, determined by the vacuum melting method. Grains of the α -phase which are separated from the β -phase later, during cooling of the plate after the completion of rolling, do not acquire a



A) Percentage of N for the interval 0.4%AL ^{c1} of 0.1%V.

Fig. 2. Interval series graphs of alloying element distribution: a - in the Ti-Al alloy plate with a striated macrostructure; *δ* and *ε* - in the Ti-Al-V alloy plate with a fine-grained polyhedral macrostructure: — — — — over the plane zx; - - - - over the plane xy. N is the number of determinations (a spectral analysis was performed for a spot diameter of about 0.1 mm)

predominant crystallographic orientation, and, furthermore, have proven to be oxygen impoverished. Since these



A) number of measurements for the interval $\Delta HV=8 \text{ kg/mm}^2$
 B) percentage of N for the interval $\Delta HV=8 \text{ kg/mm}^2$

Fig. 3 Interval series graphs of the HV hardness distribution over the planes yz and xy in the Ti-Al alloy plate: a - plate No. 1 with a striated macrostructure; б - plate No. 2 with a fine-grained polyhedral macrostructure (results along the curves are given in percentages of N, along the histograms - in the number of measurements per interval)

disoriented grains comprise most of the metal's bulk, none of the crystallographic directions is clearly recorded in the metal of the hot rolled plate as predominant.

The action of this mechanism of oriented oxygen redistribution in the metal of hot rolled plate is confirmed by the increase in the microhardness of α -grains with an increase in the average oxygen content in specimens of Ti-Al alloys, water quenched immediately after the completion of hot rolling in the $\alpha + \beta$ - region. The direct consequence of the action of this mechanism, as shown in Fig. 1, is an increase in the anisotropy of the mechanical properties of the plate's metal as its oxygen content increases.

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The relative static distribution of alloying elements in the plate metal of the test alloys Ti-Al and Ti-Al-V in the planes zx and xy, based on spectral analysis data, are shown in Fig. 2 in the form of interval distribution series graphs, as cited in reference [5]. The plate of the Ti-Al alloy had a striated macrostructure, while the plate of the Ti-Al-V alloy had a fine-grained polyhedral macrostructure without striation. In the first plate (Ti-Al) the aluminium content over the plane zx is somewhat higher than that over the plane xy (here

and subsequently determinations of the aluminium content over the plane xy were carried out in the middle layer over the thickness of the plate.) In the second plate (Ti-Al-V) there was no difference in aluminium content in each plane; the vanadium content over the plane zx , however, was higher than that over the plane xy .

In the plate of the Ti-Al alloy (Fig. 2, a) with a striated macrostructure the anisotropy carrier is obviously the macrotecture, which is intensified by the irregular chemical composition and microdefect distribution, while in the plate of the Ti-Al-V alloy (Fig. 2, δ and ϵ) with a fine-grained polyhedral macrostructure the anisotropy is carried by the physical and chemical inhomogeneities, which, like the macrostructure, are a peculiar "memory mechanism", recording in the metal the history of its thermal plastic treatment with characteristic inhomogeneous temperature, stress and deformation fields*.

It might be noted that in the two-phase alloy Ti-Al-V the anisotropy carrier is the β -stabilizer, vanadium, which has a greater tendency towards an oriented irregularity of distribution (Fig. 2, ϵ).

*See the previous article.

The presence in metal with a striated macrostructure of flattened (flatly oriented) inhomogeneities in the plate's plane is confirmed by interval series graphs for the distribution of HV hardness values over the planes yz and xy (Fig. 3) as compared with the average HB hardness values. The maximum HV hardness value distribution (Fig. 3, a) over the plane yz of plate No. 1 (Ti-Al) with a developed deformation macrostructure occurs in the interval 202-210 kg/mm², in which the HB hardness value (207 kg/mm²) is also located. The maximum HV hardness distribution over the plane xy lies in a smaller value interval (194-202 kg/mm²) than the HB (207 kg/mm²). The maximum HV hardness distributions both over the plane yz and over the plane xy of plate No. 2 (Ti-Al) without a developed deformation macrostructure are also shifted into the region of lowered values as compared with HB values (217 kg/mm²).

This is accounted for by the fact that in the presence in plate No. 1 of fine, flatly oriented inhomogeneities, caused by the macrostructure and oriented distribution of alloying and impurity elements, the Brinell ball encounters each time during indenting in the plane yz the resistance of the densely packed harder impurities moving out into the plane of the lateral edges, which the Vicker's

pyramid, having a smaller surface, falls on the less hard spots. However, most measurements (the maximum on the distribution curve) are accounted for by the relatively more frequent harder spots, since the softer spots in the plane yz have been flattened to a greater degree and have a smaller area, than the harder ones.

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In the plane xy the inhomogeneities, flattened by deformation during rolling, form spots of various hardnesses, whose dimensions are larger than those in plane yz. There is, therefore, a relatively high probability that during measurements Vicker's pyramid will fall both on the harder and the softer spots. At the same time Brinel's ball continues to rest on the harder spots, since in this case the surface of its indentation exceeds the dimensions of the inhomogeneities. As a consequence of this the HB hardness value in the plane xy of plate No. 1 remains at the same level as that in the plane yz, while the maximum HV hardness distribution shifts to a smaller value region (194-202 kg/mm²).

One may similarly explain the identical result of hardness distribution over the planes yz and xy of plate No. 2 of the Ti-Al alloy, rolled to a polyhedral macro-

structure, identical in both planes.

Conclusions

1. It has been confirmed experimentally that in hot rolled titanium alloy plate predominant crystallographic orientation does not develop and that the basic contribution to the formation of the anisotropy of the mechanical properties is made by the deformation macrotexture, which is intensified by oriented chemical composition inhomogeneities.

2. It has been demonstrated that the content of normalized impurities (oxygen, etc.) affects the development of the anisotropy of the mechanical properties of hot rolled plate. In order to ensure minimal anisotropy, the average oxygen impurity content in plate of the α -alloy (Ti-Al) should not exceed 0.09%.

3. Alloying elements make a certain contribution to the formation of the anisotropy of the mechanical properties, since the irregularity of their content over the bulk of the metal of hot rolled plate of the titanium alloys, Ti-Al and Ti-Al-V, may be of an oriented nature.

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