United States Patent Office 3,575,736
Patented Apr. 20, 1971

3,575,736

METHOD OF ROLLING TITANIUM ALLOYS

John M. Fitzpatrick, Los Altos, and Aloysius T. Davinroy, Redwood City, Calif., assignors to the United States of America as represented by the Secretary of the Air Force

No Drawing. Filed Nov. 25, 1968, Ser. No. 778,760
Int. Cl. B21b *1/00, 3/00;* B21d *31/00;* C21d *1/00*
U.S. Cl. 148—11.5 3 Claims

ABSTRACT OF THE DISCLOSURE

A method for enhancing the strength to density ratio of alpha-beta type titanium alloys. The increased strength demonstrated by the alloys of this invention is achieved by favorably altering the crystallographic texture of the alloy. The alloy to be textured is hot rolled in at least three different orientations at a temperature within a range of from about 700° to 1500° F. This results in a reduction in the cross-sectional area of the alloy by about 60 to 90%.

BACKGROUND OF THE INVENTION

This invention relates to a method for hot rolling titanium-base alloys. More particularly, this invention concerns itself with achieving favorable crystallographic texture in titanium-base alloys of the alpha-beta type by subjecting the alloy material to a multi-directional rolling process.

The formulation and fabrication of alloy materials characterized by high strength-to-density ratios has become a problem of paramount importance with the recent advances made in rocket technology. The need for such materials is obvious if further technical advances are to be made. Attempts to fully utilize the inherent potential of titanium alloys to achieve strength-to-density ratios comparable to ratios of fiberglass composites for rocket motor applications has not been successful. It is well known that deformation processing in a combination with heat hardening significantly improves the strength of metal alloys. Amongst titanium alloy the crystallographic texture which is most desirable for providing strength is one in which the basal planes of the hexagonal-alpha-phase lattice are preferentially parallel to the plane of the sheet. This texture provides strength under biaxial stress conditions greater than those in a crystallographically isotropic metal of the same composition. The all alpha alloys of titanium display this classical basal plane texturing after unidirectional rolling but these alloys do not have the potential of being heat treated in order to provide increased strength.

The alpha-beta type titanium alloys are generally rolled in one direction at temperatures of about 1700° F. with resultant textures giving rise to a less-than-isotropic biaxial strength. Although these alloys have not been considered ideally suited for texture hardening, some strength improvement can be achieved through heat hardening. The ability to properly texture harden and significantly improve the strength of alpha-beta titanium alloys is of extreme importance if the maximum utilization of titanium metal is to be realized for rocket motor applications. Previous

methods of texture hardening by straight rolling, as above, and shear spinning have so far not shown any significant increase in the textured properties of these alloys.

With the present invention, however, it has been found that a heat-treatable, texture-hardened titanium alloy suitable for use in rocket motor cases can be fabricated by subjecting a sheet of the alloy to a multi-directional rolling process preferably at temperatures not to exceed about 1300° F. The alloy work piece is rolled in a direction parallel with respect to the rolling direction. After each successive rolling pass, the work piece is rotated 45° and then reheated. This provides a multi-directional rolling process in which the work piece is rolled in three orientations with respect to the rolling direction: parallel to the rolling direction, transverse to the rolling direction, and at an angle of 45° or diagonal to the rolling direction.

The texture hardening multidirectional rolling process of this invention provides a means for utilizing the full potential of alpha-beta type titanium alloys by favorably altering the crystallographic texture of the alloy. The resultant alloy possesses higher strength under biaxial stress conditions and consequentially enable the fabrication of lighter weight structures.

SUMMARY OF THE INVENTION

In accordance with this invention, texture hardening of alpha-beta type titanium alloys can be accomplished by multi-directional rolling process in which alloy metal sheets are hot holled in three different orientations at temperatures ranging from about 700° F to 1500° F. The sheets are subjected to successive rolling operations, each of which is alternately oriented along three different directions with respect to the rolling direction: parallel to the rolling direction, transverse to the rolling direction, and at a 45° angle or diagonal to the rolling direction.

Texture hardening in accordance with the process of this invention results in a significant improvement in the strength to weight ratios of alpha-beta titanium alloys as compared to the results achieved by previously known hardening processes. After multi-directional rolling, the alloys display the favorable basal plane texturing in which the basal planes of the hexagonal-alpha-phase lattice are preferentially oriented parallel to the plane of the sheet. This results in the fabrication of a high strength alpha-beta type titanium alloy.

Accordingly, the primary object of this invention is to provide a method for favorably texturing alpha-beta titanium alloys by preferentially orienting the basal plane of the alloy's crystal lattice parallel to the plane of the sheet.

Another object of this invention is to provide a method for fully utilizing the inherent characteristics of titanium alloys to achieve high strength-to-density ratios.

Still another object of this invention is to provide a method for inducing high strength in alpha-beta type titanium alloys through a combination of processing parameters which includes heat treating and deformation-processing.

The above and still further objects and advantages of this invention will become apparent upon consideration of the following detailed description thereof;

DESCRIPTION OF THE PREFERRED EMBODIMENT

The present invention is predicated on the discovery that the crystallographic texture of alpha-beta titanium alloys can be favorably altered to produce a classical basal plane texture in order to provide an alpha-beta type titanium alloy having a high strength to density ratio. The favorable alteration is achieved by subjecting an alloy work piece to a series of hot rolling steps oriented in three different directions to reduce its cross-sectional area. The cross-sectional area is ultimately reduced by about 60 to 90 percent and the rolling steps are conducted at temperatures of from about 700 to 1500° F. Preferably the work piece is rolled at a temperature of about 1300° F. and reduced in cross-sectional area by about 90 percent.

Specific examples of alpha-beta type titanium alloys subjected to the rolling process of this invention were of two compositions, Ti-6Al-4V and Ti-7Al-2.5Mo. The Ti-6Al-4V alloy was obtained in the form of ¾ in.-thick strip, 6 in. wide. It had been a ring-rolled forging with a wall thickness of approximately 1½ in. The ring was cut open, straightened on a forge press at 1750° F., and then rolled from a furnace temperature of 1750° F. to ¾ in. thick. This strip was conditioned to remove oxide and surface irregularities by machining 1/16 in. from both surfaces. The resulting plate, ⅝ in. thick, was used for processing in accordance with this invention. A second form of a Ti-6Al-4V alloy used in the rolling process was 1½ in.-thick plate.

The Ti-7Al-2.5Mo alloy was obtained in the form of 2-in. thick plates. This material was converted to thicknesses that could be used on a two-high Fenn rolling mill. Conversion was performed in two ways by a vendor forge shop. The first way was to roll slabs from 2 in. thick to approximately 1 in. thick at a furnace temperature of 1750° F. The second way was to hammer-forge some of the 2-in. thick material to approximately 1 in. thick, also at a furnace temperature of 1750° F. The rolled material was further reduced by rolling on the Fenn mill to ⅝-in. thickness at a furnace temperature of 1750° F. Both the rolled and forged materials were used in preparing multi-directional rolled sheet for test evaluation.

The starting size of the work piece multi-directional rolling was a regular octagon, 4½ in. across the parallel edges. These starting blanks were prepared from the thick plates (1½-in. thick Ti-6Al-4V and 1-in. thick Ti-7Al-2.5Mo) by cutting the required shape on an abrasive cut-off wheel. Typical rolling schedules are illustrated in Tables I and II for Ti-6Al-4V and Ti-7Al-2.5Mo respectively. On each successive rolling pass, the octagon was rotated 45° and reheated after every pass.

When the size of the work piece reached an effective diameter of 9 in., the octagonal plate was cut into two equal sections from each of which was prepared another regular octagon measuring approximately 4½ in. across. These pieces were then multi-directionally rolled in the same manner as before to a final thickness of approximately ⅛ in. A production summary of multi-directional rolling is given in Table III.

TABLE I

[Multi-directional rolling schedule for Ti-6Al-4V; Preheat Temperature 1,300° F.]

Pass No.	Material thickness	Percent/ pass	Exit temp. (° F.)	Remarks
--------	1.500	----------		Preheat block for 1 hr. at 1,300° F.
1-------	1.469	2.0	1,040	
2-------	1.416	3.7	--------	
3-------	1.372	3.1	--------	
4-------	1.322	3.6	--------	
5-------	1.223	7.0	1,050	
6-------	1.171	4.3	1,020	
7-------	1.120	4.4	1,020	
8-------	1.071	4.4	1,040	
9-------	1.020	4.8	1,060	
10------	0.965	5.4	--------	

TABLE I.—Continued

Pass No.	Material thickness	Percent/ pass	Exit temp. (° F.)	Remarks
11------	0.918	4.3	--------	
12------	0.871	5.1	1,040	
13------	0.820	5.9	--------	
14------	0.769	6.2	1,020	
15------	0.722	6.1	--------	
16------	0.672	6.9	1,000	
17------	0.625	7.0	--------	
18------	0.571	8.6	1,000	
19------	0.532	6.8	--------	
20------	0.508	4.5	960	
21------	0.470	7.4	1,000	Slight dishing of plate occurred on 21st pass and persisted through final pass.
22------	0.445	5.3	--------	
23------	0.426	4.3	980	
24------	0.406	4.7	--------	
25------	0.389	4.7	1,000	
26------	0.365	5.7	--------	
27------	0.347	4.9	1,000	Air-cool plate. Plate was cut in half to enable continued rolling. Preheat both plates at 1,300° F. for 30 min.
28------	0.331	4.6	--------	
29------	0.316	4.5	960	
30------	0.297	6.0	920	
31------	0.281	5.4	930	
32------	0.268	4.6	890	
33------	0.253	5.6	900	
34------	0.239	5.5	900	
35------	0.228	4.6	900	
36------	0.218	4.4	900	
37------	0.206	5.5	890	
38------	0.200	2.3	840	
39------	0.187	6.5	840	
40------	0.175	6.4	860	
41------	0.168	4.0	860	
42------	0.156	7.1	840	
43------	0.139	8.5	820	
44------	0.136	2.2	800	
45------	0.130	4.3	780	
46------	0.127	2.3	--------	Air-cool after final pass.

TABLE II

[Multi-directional rolling schedule for Ti-7Al-2.5Mo; preheat temperature 1,450° F.]

Pass No.	Material thickness	Percent/ pass	Exit temp. (° F.)	Remarks
--------	1.000	----------		Preheat block at 1,450° F. for 1 hr.
1-------	0.926	5.6	1,100	
2-------	0.871	5.9	1,100	
3-------	0.818	6.1	1,130	
4-------	0.768	6.1	1,100	
5-------	0.722	6.0	1,100	
6-------	0.679	6.0	--------	
7-------	0.637	6.2	1,100	
8-------	0.600	5.8	1,100	
9-------	0.563	6.2	1,100	
10------	0.530	5.9	--------	
11------	0.498	6.0	1,080	
12------	0.467	6.2	--------	
13------	0.440	5.8	1,070	
14------	0.414	5.9	--------	
15------	0.390	5.8	1,040	
16------	0.367	6.0	1,040	
17------	0.344	6.3	1,040	
18------	0.326	5.2	1,040	
19------	0.307	5.8	1,040	
20------	0.290	5.5	980	Slight dishing of plate occurred on 20th pass and persisted through final pass.
21------	0.272	6.2	--------	
22------	0.262	3.7	1,020	Air-cool plate. Plate was cut in half to enable continued rolling. Preheat both plates at 1450° F. for 30 min.
23------	0.249	5.0	940	
24------	0.234	6.0	960	
25------	0.221	5.0	--------	
26------	0.210	5.0	900	
27------	0.200	4.8	900	
28------	0.188	6.0	940	
29------	0.182	3.2	940	
30------	0.173	5.0	--------	
31------	0.164	5.2	800	
32------	0.155	5.5	880	
33------	0.148	4.5	880	
34------	0.143	3.4	860	
35------	0.136	4.9	--------	
36------	0.129	5.1	840	
37------	0.127	1.6	840	
38------	0.123	3.1	800	Air-cool sheet after final pass.

TABLE III

Ti-6 Al-4V and Ti-7Al-2.5Mo multi-directional roll production summary]

Alloy	Sheet designation	Material starting thickness (in.)	Preheat temp. (° F.)[1]	Total reduction (percent)	Total rolling passes	Remarks
Ti-6Al-4V	3SRR	1.5	1,300	93	47	Two plates obtained with a diameter of 8 in.
Ti-6Al-4V	4SRR	1.5	1,300	91.5	49	Four plates obtained with a diameter of 7¼ in.
Ti-6Al-4V	8SRR	0.624	1,300	80	25	Straight rolled at furnace temperature 1,700° F. from 1½ in. thick to 0.625 in. prior to round rolling. Two finished plates obtained with diameter of 8½ in.
Ti-6Al-4V	10SRR	0.624	1,100	80	27	Do.
Ti-6Al-4V	13SRR	0.370	1,300	70	20	Straight rolled at furnace temperature 1,700° F. from 1¾-in. thick to 0.370 in. prior to round rolling. Two finished plates obtained with diameter of 7¼ in.
Ti-6Al-4V	15SRR	0.370	1,100	70	22	Do.
Ti-6Al-4V	17SRR	1.5	1,400	92	43	Two plates obtained with a diameter of 7¼ in.
Ti-6Al-4V	19SRR	1.5	1,500	92	40	Do.
Ti-7Al-2.5Mo	12SRR	0.620	1,400	80	24	One plate obtained with a diameter of 10 in.
Ti-7Al-2.5Mo	21SRR	1.000	1,450	87	38	Do.

[1] The preheat temperature is that at which the material was allowed to soak. This soaking was performed in a 40 kw. resistance box furnace for 15 min. prior to each rolling pass. Whenever the material was allowed to air cool, it was preheated for a period of not less than 30 mn. prior to the next rolling pass.

No conditioning was necessary for the Ti-6Al-4V alloys other than that described heretofore. The 1½ in. thick plate was received as bright, flat, and locally conditioned material. The hammer-forged Ti-7Al-2.5Mo alloy required milling approximately 1/16 in. from both surfaces to prepare clean, flat surfaces for rolling.

All rolling procedures were done on a Fenn, type 081, two-high rolling mill. The mill had a ground, roll-face width of 9 in. Unidirectional rolling (also termed straight rolling) was conducted on starting plates (sheet-bars) of the Ti-6Al-4V having the following dimensions: 7½ by 8¾ by 1½ in. Unidirectional rolling was carried out with the 7½-in. dimension in the rolling direction. Rolled sheets were edge trimmed by shearing or abrasive wheel cutting to 8-in. widths in order to pass through the Stanat Roller Leveler. The roller-leveler was employed following the final roll pass to achieve necessary flatness in the sheets. In some cases, the work had a tendency to curl on exit from the rolls, particularly at thicknesses between ½ and ¼ in. When this occurred, it was necessary to flatten the pieces on a hydraulic press between platens. Prior to a flattening or roller leveling operation, the work was heated to the same temperature as it would be for a rolling pass. Typical unidirectional rolling schedules are shown in Tables IV and V and were conducted to provide comparative results achieved between unidirectional and multi-directional rolling. All rolling was done at a constant roll speed of 29 ft./min., which was chosen only for convenience in handling the material on exit from the mill. The actual temperature of the metal on exit from the rolls was monitored periodically with a surface-contact pyrometer. The work was reheated to the furnace temperature after each pass. Percentage reduction per pass was determined by a limit imposed by the strength of shear pins in the drive train of the rolling mill. A production summary of straight rolling is given in Table VI.

TABLE IV

[Unidirectional rolling schedule for Ti-6Al-4V; preheat temperature 1,100° F.]

Pass No.	Material thickness	Percent/ pass	Exit temp. (° F.)	Remarks
------	1.522	------		Preheat block at 1,100° F. for 1 hr.
1	1.496	1.7	------	
2	1.478	1.2	------	
3	1.458	1.3	------	
4	1.441	1.2	------	
5	1.421	1.4	------	
6	1.401	1.4	------	
7	1.381	1.0	------	
8	1.365	1.16	------	
9	1.343	1.6	940	
10	1.324	1.55	900	
11	1.306	1.36	900	
12	1.286	1.5	900	
13	1.264	1.7	900	
14	1.245	1.5	900	
15	1.223	1.77	900	
16	1.202	1.7	------	
17	1.181	1.75	940	
18	1.162	1.6	------	
19	1.141	1.84	920	
20	1.121	1.75	920	
21	1.102	1.7	------	
22	1.081	1.9	920	
23	1.062	1.75	------	
24	1.041	1.98	900	
25	1.014	2.6	------	
26	0.997	1.68	910	
27	0.980	1.7	------	
28	0.959	2.1	900	
29	0.938	2.2	------	
30	0.917	2.3	900	
31	0.897	2.2	------	
32	0.877	2.2	900	
33	0.868	------		
34	0.855	1.5	------	
35	0.836	2.2	------	
36	0.816	2.4	900	
37	0.796	2.4	------	
38	0.778	2.3	900	
39	0.758	2.6	900	
40	0.738	2.6	------	Press-straighten plate after 40th pass.
41	0.718	2.7	900	
42	0.700	2.5	------	Press-straighten plate after 42nd pass.
43	0.676	3.4	920	
44	0.658	2.7	------	Press-straighten plate after 44th pass.
45	0.639	2.9	920	
46	0.621	2.7	------	Press-straighten plate after 46th pass.
47	0.601	3.2	920	
48	0.583	3.0	------	Press-straighten plate after 48th pass.
49	0.564	3.3	------	
50	0.550	2.5	900	Press-straighten plate after 50th pass.
51	0.531	3.3	920	
52	0.516	2.8	------	Press-straighten plate after 52nd pass. Plate now measures 26½ in. long and will be cut in half for continuation of rolling.
53	0.500	3.1	820	
54	0.483	3.4	900	Press-straighten plate after 54th pass.
55	0.469	2.9	900	
56	0.456	2.8	880	
57	0.441	3.3	880	Press-straighten plate after 57th pass.
58	0.428	3.0	860	
59	0.414	3.3	860	
60	0.400	3.4	880	
61	0.389	2.8	880	Press-straighten plate after 61st pass.
62	0.375	3.6	880	
63	0.365	2.7	880	
64	0.351	3.8	------	Press-straighten plate after 64th pass.
65	0.345	1.7	------	
66	0.337	2.3	840	
67	0.324	3.9	880	
68	0.317	2.2	860	
69	0.305	3.8	880	
70	0.293	3.9	860	
71	0.282	3.8	800	
72	0.270	4.2	880	
73	0.262	3.0	860	
74	0.253	3.4	860	
75	0.241	4.7	------	
76	0.230	4.6	840	
77	0.220	4.3	820	
78	0.210	4.5	820	
79	0.199	5.2	820	
80	0.189	5.0	820	
81	0.179	5.3	------	
82	0.168	6.1	820	
83	0.157	6.5	800	
84	0.149	5.1	780	Air-cool sheet after final pass.

TABLE V

[Unidirectional rolling schedule for Ti-6Al-4V; preheat temperature 1300° F.]

Pass. No.	Material thickness	Percent/ pass	Exit temp. (° F.)	Remarks
-------	1.500	-------	-------	Preheat block for 1 hr. at 1300° F.
1-------	1.448	-------	1,050	
2-------	1.426	2.2	1,050	
3-------	1.380	3.2	-------	
4-------	1.332	3.48	1,050	
5-------	1.280	3.9	-------	
6-------	1.230	3.9	1,050	
7-------	1.180	4.1	-------	
8-------	1.127	4.5	1,050	
9-------	1.079	4.25	-------	
10------	1.030	4.5	1,050	
11------	0.977	5.1	-------	
12------	0.926	5.2	1,050	
13------	0.877	5.3	-------	
14------	0.828	5.6	-------	
15------	0.775	6.4	-------	
16------	0.725	6.5	-------	
17------	0.676	6.75	-------	
18------	0.629	6.9	-------	
19------	0.594	6.5	-------	Press-straighten plate after 19th pass.
20------	0.559	5.9	-------	
21------	0.522	6.6	-------	
22------	0.494	5.4	-------	Press-straighten plate after 22nd pass.
23------	0.464	6.1	-------	
24------	0.438	5.6	-------	
25------	0.409	6.6	-------	Press-straighten plate after 25th pass.
26------	0.384	6.1	-------	
27------	0.362	5.7	-------	Press-straighten plate after 27th pass.
28------	0.342	5.5	-------	
29------	0.320	6.4	-------	
30------	0.308	3.8	-------	
31------	0.302	4.7	980	Press-straighten plate after 31st pass.
32------	0.284	6.0	980	
33------	0.270	4.9	960	Press-straighten plate after 33rd pass.
34------	0.252	6.7	-------	Press-straighten plate after 34th pass.
35------	0.235	6.7	-------	
36------	0.223	5.1	-------	
37------	0.209	6.3	900	
38------	0.195	6.7	-------	
39------	0.183	6.2	840	
40------	0.171	6.5	880	
41------	0.159	7.0	-------	
42------	0.152	0.4	-------	Air-cool sheet after final pass.

TABLE VI

[Ti-6Al-4V unidirectional sheet production summary]

Sheet designation	Material starting thickness (in.)	Preheat temp. (°F.) [1]	Total reduction (percent)	Total rolling passes	Remarks
15791-1	1.5	1,300	90	44	Sheet length, 65 in.
15791-2	1.5	1,100	89	97	Slight surface cracking noted on finished sheet. Sheet length, 72 in.
15791-3	1.5	1,300	90	42	Sheet length, 75 in.
15791-4	1.5	1,300	90	42	Sheet length, 76 in.
15791-4A	0.150	RT	10	8	15791-4 sheet was cut in 2 pieces. One piece 37 in. long was solution treated at 1600° F.-15 min. and WQ, followed by 10% cold reduction
15791-4B	0.150	RT	10	7	Second sheet, 39 in. long, from 15791-4 was solution treated at 1,700° F.-15 min. and WQ, followed by a 10% cold reduction.
15791-2A	0.152	RT	10	7	15791-2 sheet was cut in 2 pieces solution treated at 1700° F.-15 min. and WQ, followed by a 10% cold reduction.
15791-5	1.5	1,100	90	87	Slight surface cracking noted on fininshed sheet. Sheet length, 83 in.

[1] The preheat temperature is that at which the material was allowed to soak. This soaking was performed in a 40 kw. resistance box furnace for 15 min. prior to each rolling pass. Whenever the material was allowed to air cool, it was preheated for a period of not less than 30 min. prior to the next rolling pass.

In the following tables of data summarizing the uniaxial tension test results for the alloys of this invention, the notation "R" indicates a practical measure of the texture achieved by any thermal-mechanical process. It measures the ratio of the plastic lateral strains, at 0.2% longitudinal plastic strains, measured in a uniaxial tension test performed on the alloy work piece regardless of the angular relation of the major axis of the work piece to the rolling direction. "R" is defined either as ϵ_w/ϵ_t or, alternatively, as $d\epsilon_w/d\epsilon_t$ where ϵ_w is the natural or logarithmic strain measured in the width dimension, and ϵ_t is the similar measurement in the thickness dimension of the uniaxial tension test work piece. The same notation "R" is also used in the following discussion.

Uniaxial tension test data for the 5/8-in.-thick Ti-6Al-4V alloy material are presented in Table VII. Here, the uniaxial test data for the as-received plate, as well as data on straight-rolled and multi-directional rolled plates are shown. On the basis of the R values, this material appears to be capable of developing substantial textures during rolling to a total reduction of about 80%.

Uniaxial tension test data for the Ti-7Al-2.5Mo alloy in the hammer-forged condition are presented in Table VIII. In this case, we find that R is slightly greater than 1, and that substantial R values are achieved by multi-directional rolling to total reductions of less than 90%.

TABLE VII

Uniaxial tension data on preliminary material (Ti-6Al-4V) in indicated condition

	Longitudinal
Yield strength at 0.2% (k.s.i.)	102.2
Engineering tensile strength (k.s.i.)	142.0
Young's modulus (p.s.i.$\times 10^{-6}$)	13.45
Plastic strain at maximum load (percent)	4.6
Total elongation (2-in. gage) (percent)	13.3
Elastic Poisson's ratio	0.349
R at 0.2% long. plastic strain	0.8
Calculated 1:2 biaxial YS (k.s.i.)	113.6

As-received.

Yield strength at 0.2% (k.s.i.)	150.3
Engineering tensile strength (k.s.i.)	168.7
Young's modulus (p.s.i.$\times 10^{-6}$)	14.8
Plastic strain at maximum load (percent)	2.6
Total elongation (2-in. gage) (percent)	4.0
Elastic Poisson's ratio	0.393
R at 0.2% long. plastic strain	3.07
Calculated 1:2 biaxial YS (k.s.i.)	214.0

Straight rolled~80% furnace temperature 1100° F., as-rolled.

	Annealed at 1,400° F.-1 hr.	Annealed 1,400° F.-1 hr., ST 1,800° F.-¼ hr. WQ, aged at 900° F.-24 hr.
Yield strength at 0.2% (k.s.i.)	134.2	164.0
Engineering tensile strength (k.s.i.)	136.2	184.0
Young's modulus (p.s.i.$\times 10^{-6}$)	15.6	18.5
Plastic strain at maximum load (percent).	>8	2.2
Total elongation (2-in. gage) (percent)	20.8	3.9
Elastic Poisson's ratio	0.443	0.349
R at 0.2% long. plastic strian	3.19	1.46
Calculated 1:2 biaxial YS (k.s.i.)	192.1	202.5

NOTE.—Multi-directional rolled~80%; furnace temperature 1,300° F.

TABLE VIII

[Uniaxial tension data on Ti-7Al-2.5Mo alloy]

Mechanical property	Conditions A		B	C
Yield strength at 0.2% (k.s.i.)	108.3	134.2	136.2	137.4
Engineering tensile strength (k.s.i.)	121.8	156.5	157.2	155.3
Young's modulus (p.s.i.×10-6)	16.2	16.4	16.0	16.45
Plastic strain at maximum load (percent)	~4	4	2.5	3.6
Total elongation (2-in. gage) (percent)	13.5	9.6	9.2	10.3
Elastic Poisson's ratio, μE	0.368	0.420	0.382	0.388
R at 0.2% longitudinal plastic strain	1.17	4.3	4.6	4.0
Calculated 1=2 biaxial YS (k.s.i.)	128.5	203.0	208.1	204.8

Explanation of conditions: A—Hammer forged from 2-in. thick plate to 1-in. thick plate, furnace temp. 1,750° F. (as received). B—Material A, multidirectional rolled, furnace temp. 1,450° F. from 1 in. thick to ⅛ in. thick. Annealed at 1,400° F.–1 hr., ST at 1,750° F.–¼ hr., WQ plus age at 900° F.–24 hr. C—Straight rolled from 1-in. thick plate to ⅝-in. thick plate furnace temp. 1,750° F. Subsequently multi-directional rolled furnace temp. 1,400° F. from 0.621 in. to 0.125 in. Annealed at 1,400° F.–1 hr., ST at 1,750° F.–¼ hr. WQ plus age at 900° F.–24 hr.

Plastic strain at maximum load (percent)	5
Total elongation (2-in. gage) (percent)	6.5
Elastic Poisson's ratio	0.359
R at 0.2% long. plastic strain	1.98
Calculated 1:2 biaxial YS (k.s.i.)	192.8

Rolled 1500° F., annealed 1400° F., STA

Mechanical property:

Yield strength at 0.2% (k.s.i.)	147.5
Engineering tensile strength (k.s.i.)	165.6
Young's modulus (p.s.i.×10−6)	15.6
Plastic strain at maximum load (percent)	2.8
Total elongation (2-in gage) (percent)	8.6
Elastic Poisson's ratio	0.356
R at 0.2% long. plastic strain	1.75
Calculated 1:2 biaxial YS (k.s.i.)	188.2

The uniaxial tension test work pieces were instrumented with strain gages to provide the test results. Initially, six strain gages were employed; two in the width dimension, on opposite faces; two in the thickness dimension on opposite edges; and two in the longitudinal dimension, on opposite faces. One-sixteenth-inch gage length, foil-type strain gages were used in the thickness direction and one-eighth-inch gage length foil-type strain gages were used in the length and width directions. All gages were bonded to the specimen surface with Eastman 910 contact adhesive. A 2-in. gage length extensometer was also employed as a check of longitudinal strain. During each test, the load, the extensometer, and the six strain gages were read-out on eight channels of a light-beam oscillograph. From the resulting data, lateral strain ratios were calculated at a number of points following the onset of plastic deformation.

From a comparison examination of the test results disclosed in Tables IX and X, it can be seen that the multi-directional rolling process of this invention provides an alpha-beta type titanium alloy having a high strength to density ratio as indicated by the calculated R values. Table XI presents data resulting from a multi-directional rolling process conducted at temperatures of 1400° F. and 1500° F., respectively.

The invention has been described with particular reference to specific embodiments thereof. It is to be under-

TABLE IX

[Uniaxial tension data on Ti-6Al-4V, straight rolled, 90% reduction]

	As-rolled, 90% reduction [1]			Annealed at 1,400°.-1 hr.			Annealed at 1,400° F.-1 hr. plus STA			ST 1,700° F.-¼- hr. WQ, aged at 900° F.-24 hr.		
	Longitudinal	Diagonal	Transverse	Longitudinal	Diagonal	Transverse	Longitudinal	Diagonal	Transverse	Longitudinal	Diagonal	Transverse
Yield strength at 0.2% (k.s.i.)	127.0	126.0	140.0	126.0	124.0	141.0	145.2	145.0	153.0	158.2	146.0	150.6
Engineering tensile strength (k.s.i.)	152.2	128.0	146.7	151.0	127.5	146.0	171.5	159.0	172.0	179.8	162.0	172.0
Young's modulus (p.s.i.×10-6)	14.9	18.3	17.3	15.15	16.35	19.0	15.75	16.8	15.75	15.9	16.65	16.8
Plastic strain at maximum load (percent)	5.8	5.7	2.2	>8.0	>8.0	5.0	3.6	4.0	2.4	4.8	~3.0	5.0
Total elongation (2 inches gage) (percent)	9.0	17.8	4.5	18.1	18.5	14.2	10.4	11.0	8.7	7.1	11.0	10.3
Elastic Poisson's ratio	0.350	0.378	0.395	0.341	0.380	0.406	0.353	0.391	0.391	0.317	0.346	0.334
R at 0.2% longitudinal plastic strain	1.33	4.08	0.9	1.17	4.2	0.83	1.66	3.32	1.76	0.85	2.0	1.22
Calculated 1:2 biaxial YS (k.s.i.)	154.0	188.2	158.8	149.7	186.5	158.0	183.5	208.5	195.2	177.6	191.0	180.0

[1] From furnace temperature of 1,300° F.

In performing the several rolling schedules, the primary objective has been to achieve the highest possible lateral strain ratios through the development of a favorable crystallographic texture. Such a texture gives rise to high lateral strain ratios in uniaxial tension tests performed on work piece samples taken parallel to the rolling direction and transverse to the rolling direction. Thus, from the sheet materials that were rolled, emphasis was placed on measuring R in the rolling direction.

On the basis of a heat-treatment study and an indication that a 1400° F. anneal stabilizes the crystallographic texture, a standard heat treatment (STA) was adopted so that the influence of other processing parameters might be noted. This treatment consisted of a 1400° F.-1 hr. anneal, a 1700° F. solution treatment for ¼ hr., water quenching, and aging at 900° F. for 24 hr.

TABLE X

[Uniaxial tension data on Ti-6Al-4V, multi-directional rolled 90%, furnace temperature 1,300° F.]

Mechanical property	As-rolled	Annealed 1,400° F.-1 hr.	Annealed 1,400° F.-1 hr., ST 1,700° F.-¼ hr., WQ, aged at 900° F.-24 hr.		ST 1,700° F.-¼ hr., WQ, Aged at 900° F.-24 hr.
Yield strength at 0.2% (k.s.i.)	121.3	110.9	146.0	143.0	148.3
Engineering tensile strength (k.s.i.)	130.8	114.5	160.5	161.0	163.1
Young's modulus (p.s.i.×10-6)	14.25	15.0	16.6	15.1	15.87
Plastic strain at maximum load (percent)	1.9	5.7	4.5	3.0	3.2
Total elongation (2-in. gage) (percent)	11.1	15.3	10.6	10.4	10.1
Elastic Poisson's ratio	0.490	0.478	0.495	0.403	0.399
R at 0.2% longitudinal plastic strain	3.35	4.72	4.94	2.94	2.26
Calculated 1:2 biaxial YS (k.s.i.)	175.1	170.0	225.5	201.4	198.7

Note.—Uniaxial tension data on Ti-6Al-4V, multi-directional rolled 90%, furnace temperature 1,300° F.

TABLE XI

Uniaxial Tension Data on Ti-6Al-4V, Multi-Directional Rolled 90% Reduction at 1400° F. and 1500° F.

Rolled 1400° F., annealed 1400° F., STA

Mechanical property:

Yield strength at 0.2% (k.s.i.)	147.5
Engineering tensile strength (k.s.i.)	166.0
Young's modulus (p.s.i.×10−6)	15.9

stood, however, that the description of the present invention is for the purpose of illustration only, and it is not intended to limit the invention in any way.

What is claimed is:

1. A method for rolling an alpha-beta titanium alloy sheet which comprises the steps of rolling said sheet to reduce its cross-sectional area by passing said sheet in a planar first direction parallel to the rolling direction in a single rolling pass while heated to temperature between about 700° F. to 1500° F., continuing said rolling until the cross sectional area of the sheet is reduced by about 60 percent to 90 percent of its original cross-sectional area by performing a plurality of such rolling passes, angularly rotating said alloy sheet in the plane of said first direction subsequent to each repeated rolling pass such that rolling is effected in at least three differently oriented directions relative to said rolling direction and then cooling said rolled sheet to room temperature.

2. A method for rolling an alpha-beta titanium alloy sheet which comprises the steps of rolling said sheet to reduce its cross-sectional area by passing said sheet in a planar first direction parallel to the rolling direction in a single rolling pass while heated to a temperature of 1300° F., continuing said rolling until the cross-sectional area of the sheet is reduced to about 90 percent of its original cross-sectional area by performing a plurality of such rolling passes, rotating said alloy sheet 45° in the

plane of said first direction subsequent to each repeated rolling pass such that rolling is effected in at least three differently oriented directions relative to said rolling direction and then cooling said rolled sheet to room temperature.

3. A method in accordance with claim 2 wherein the rolled sheet is further annealed at a temperature of about 1400° F. for one hour, solution heat treated at 1700° F. for about 15 minutes, water quenched, and aged at 900° F. for 24 hours prior to cooling to room temperature.

References Cited

UNITED STATES PATENTS

691,565	1/1902	Norton.	
2,165,027	7/1939	Bitter.	
3,169,085	2/1965	Newman	148—11.5
3,492,172	1/1970	Sauvageot et al.	148—11.5
3,496,755	2/1970	Guernsey et al.	72—364
3,489,617	1/1970	Weurfel	148—11.5

CHARLES W. LANHAM, Primary Examiner

E. M. COMBS, Assistant Examiner

U.S. Cl. X.R.

148—12.7; 72—200, 364, 365, 700