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Vacuum Creep Flattening of Titanium and Titanium Alloy Plates

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Abstract:

Titanium and titanium alloy plates are generally difficult to flatten at room temperature because of their large springback and high strength. At the annealing temperature, however, their creep strength decreases to such a level that they can be simultaneously annealed and flattened. The vacuum creep flattening (VCF) process straightens deflected titanium and titanium alloy plates by placing them on a flat bed, gradually evacuating the air while slowly heating them applying the atmospheric pressure throughout them and causing them to undergo creep deformation while fully soaking them at the annealing temperature. Since the strains introduced into the plates during fabrication are fully eliminated, residual stresses in the bulk and surface of the plates can be completely removed, and titanium products with good flatness and extremely small springback during secondary-fabrication can be produced. An overview is given on the titanium and titanium alloy plate VCF equipment that started commercial operation at the stainless steel plate mill of Yawata Works in April 1993. General specifications, straightening capacity and metallurgical property control capability of the VCF equipment and the flatness and mechanical properties of the titanium plates produced on the VCF equipment are discussed.

1. Introduction

Titanium and titanium alloy plates are widely used in airframe structures, power plant condenser tubesheets, prime metals for clad plates, electrodes and chemical plants because of their excellent corrosion resistance and high specific strength. They are hot rolled on a plate mill, heat treated, flattened and surface finished (pickled or ground) before they are marketed. Titanium and titanium alloys call for special care in their secondary fabrication. They are generally difficult to straighten because of their large springback. This is because the Young's modului of titanium and its alloys is about a half of that of steel. And they must be mildly ground and machined for long tool life. Use of high-flatness plates reduces the necessity of providing extra thickness and raises productivity and yield in the product finishing process and the secondary fabrication process at customers.

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This article describes the hardware in brief, straightening capacity and metallurgical control capability of the vacuum creep flattening (VCF) equipment that was brought on stream in April 1993 at the stainless steel plate mill of Yawata Works. Also presented are examples of the flatness and mechanical properties of titanium and titanium alloy plates produced on the VCF equipment.

Titanium and its alloys have large springback and high strength so that it is difficult to flatten them at room temperature. When a titanium or titanium alloy plate is cold leveled to desired flatness, residual stresses are introduced in the surface of the plate to maintain the flat shape. When such a cold-leveled plate is ground or chemically milled, residual stress equilibrium in the plate is broken to revive its original shape[1]. When a titanium or titanium alloy plate is heated to its annealing temperature, its creep strength decreases to the level where flattening can be accomplished simultaneously with annealing[2]. Titanium plates may be leveled by creep flattening or vacuum creep flattening. The former method employs weighting when annealing the titanium plate to flatness, and has been traditionally adopted at Nippon Steel and other plants. It did not always bring satisfactory results, however, in terms of operability, heating temperature control, size availability and product flatness. Some creep flattened plates even needed additional cold roller leveling.

The vacuum creep flattening process was developed by the Boeing Co. in order to relieve the internal and surface residual stresses of titanium and titanium alloy plates[1]. The plate is placed on a flat ceramic bed, slowly heated, exposed to a gradually increasing vacuum, subjected to the atmospheric pressure, creep deformed and flattened. The strains introduced into the plate by primary fabrication are eliminated and the internal and surface residual stresses of the plate can be completely relieved. The vacuum creep flattening technique produces titanium and titanium alloy plates that are flat and very small in springback during secondary fabrication. It is also advantageous in that it is relatively free from oxidation and contamination with foreign matters. Leading wrought titanium manufacturers in the United States have vacuum creep flattening equipment with these excellent features, but only a few reports are published on the straightening capacity and material property control capability of the VCF facilities[1,2].

2. Overview of VCF Equipment

In April 1993, vacuum creep flattening (VCF) equipment was completed and commissioned at the stainless steel plate mill of Yawata Works. Its main specifications are given in **Table 1**, its general view while in operation is shown in **Photo 1**, and its structure is schematically illustrated in **Fig. 1**. The effective furnace hearth area of 3,620 mm × 11,100 mm provides the world's largest treating capacity. The largest feature of the VCF equipment is that a fused silica ceramic bed (platen) machined to tolerances of ±0.1 mm and provided with a low coefficient of thermal expansion and high compression strength is adopted to meet the flatness requirement. A batch of titanium plates is placed on the platen and is covered with waster sheets (0.5-mm thick disposable sheets of commercially pure titanium), thermocouples, vermiculite and plastic cover sheet (nylon) (see **Fig. 1**).

Table 1 Main specifications of VCF equipment

Item	Specification	
Equipment	Startup	April 1993
	Basic design	TIMET
	Overall design and fabrication	Plant & Machinery Division, Nippon Steel
	Effective hearth area	3,620 mm wide × 11,110 mm long
	Heating method	332 150-W electric heating elements
	Temperature range	Room temperature to 815°C
	Furnace vacuum	25 mmHg (3,333 Pa)
	Temperature and heat pattern control	Full automatic direct digital control (DDC)
Capacity	Grades	Commercially pure titanium and titanium alloys
	Size	Thickness: 150 mm maximum
		Width: 3,500 mm maximum
		Length: 10,000 mm maximum
	Product flatness	1 mm/m maximum

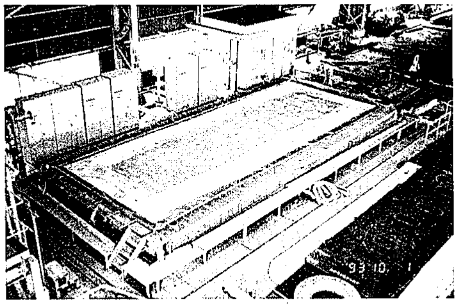


Photo 1 General view of VCF equipment in operation

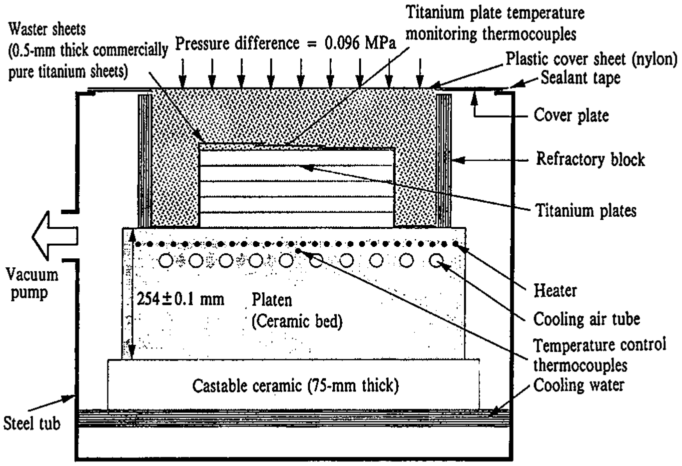


Fig. 1 Cross-section of VCF equipment

The VCF treatment doubles as annealing. The soaking temperature and time are determined to suit the grade of titanium material, plate size (thickness, width and length), initial shape, and target quality (mechanical properties and microstructure). **Fig. 2** shows a typical heating and cooling pattern for commercially pure titanium. The furnace vacuum is held at 25 to 60 mmHg (3,333 to 8,000 Pa) during the soaking period.

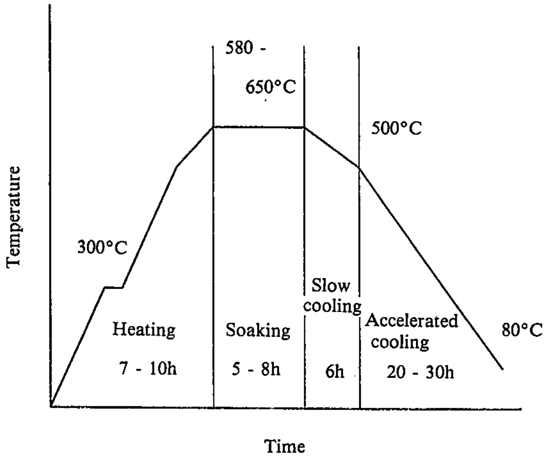


Fig. 2 Typical heat pattern of VCF treatment for commercially pure titanium

3. Study of Straightening Capacity of VCF Equipment

3.1 Numerical model of vacuum creep flattening

The strain rate $\dot{\varepsilon}$ during creep deformation is given as a function of the applied stress σ and the test time t by Eq. (1).

$$\dot{\varepsilon} = A\sigma^n t^m \qquad \cdots\cdots(1)$$

In the quasi steady-state region of primary creep[3] and the steady-state creep region, $m = 0$, so that Eq. (1) corresponds to Norton's rule. Introducing the apparent activation energy Q, the strain rate $\dot{\varepsilon}$ can be expressed by

$$\dot{\varepsilon} = A\sigma^n,\ A = B\exp(-{}^{Q}/_{RT}) \qquad \cdots\cdots(2)$$

where A and n are material constants.

Creep deformation in the quasi steady-state region of primary creep and the steady-state creep region is assumed in the numerical modelling of vacuum creep flattening. The unbending deformation of a deflected plate is simplified as follows. A rectangular plate with one side being infinitely long is assumed to be deformed by the bending moments due to the uniformly distributed load q under the atmospheric pressure (see **Fig. 3**). The deflection W of the middle surface of the plate at $x = 0$ is taken as maximum flattening height[4].

For multiaxial steady-state creep, Eq. (2) holds directly for the effective stress σ_c and effective strain rate $\dot{\varepsilon}_c$. According to Odqvist and Hult[5], Norton's equation becomes Eq. (3) for the case of **Fig. 3**.

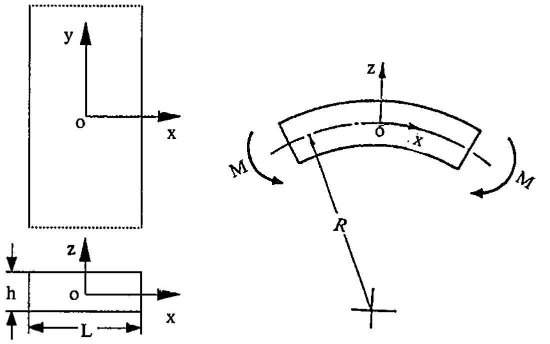


Fig. 3 Deformation of long rectangular plate by bending moment

$$\dot{\varepsilon}_x = \left(\frac{\sqrt{3}}{2}\right)^{(n+1)} A\sigma_x^n \qquad \cdots\cdots(3)$$

In the bending deformation of the plate, the bending strain ε_x at the distance z from the middle surface is expressed by Eq. (4) as a function of the curvature k and the z-direction deflection W of the plate according to classical small-deflection theory.

$$\varepsilon_x = zk = -z\frac{\partial^2 W}{\partial X^2} = -zW'' \qquad \cdots\cdots(4)$$

Taking the derivative of Eq. (4) with respect to time t and substituting it into Eq. (3) yields Eq. (5), which is the stress distribution in the thickness direction of the plate.

$$\sigma_x = A^{\left(\frac{1}{n}\right)}\left(\frac{2}{\sqrt{3}}\right)^{\left(1+\frac{1}{n}\right)}\dot{k}^{\left(\frac{1}{n}\right)} z^{\left(\frac{1}{n}\right)} \qquad \cdots\cdots(5)$$

Therefore, the relationship between the moment M per unit length and the rate of change in curvature $\dot{k}$ at the middle surface of the plate is given by Eq. 6.

$$M = 2A^{\left(\frac{1}{n}\right)}\left(\frac{2}{\sqrt{3}}\right)^{\left(1+\frac{1}{n}\right)}\dot{k}^{\left(\frac{1}{n}\right)}\left(\frac{h}{2}\right)^{\left(2+\frac{1}{n}\right)}\left(2+\frac{1}{n}\right)^{-1} \qquad \cdots\cdots(6)$$

When the uniformly distributed load q is considered to act on the plate of the length L which is simply supported at both edges, the bending moment is given by Eq. 7.

$$M = \frac{q}{2}(LX - X^2) \qquad \cdots\cdots(7)$$

From Eqs. (6) and (7), is given by Eq. 8.

$$\dot{W}'' = -A\,(3)^{\left(\frac{n+1}{2}\right)}\left(\frac{2n+1}{n}\right)^n\left(\frac{1}{h^{2n+1}}\right)\left(\frac{qL^2}{2}\right)^n\left(\frac{X}{L}-\frac{X^2}{L^2}\right)^n \qquad \cdots\cdots(8)$$

Eq. (8) is approximated by a power series and integrated twice by x to obtain the deflection rate $\dot{W}$. The change with time in the deflection W can be calculated by substituting the material constants A and n, plate size, and loading conditions. The procedure described above was implemented in section 3.3 using symbolic algebra software *MATHEMATICA* on Macintosh.

3.2 Creep data

(1) Collection of creep data as basis for estimation of straightening capacity

The VCF equipment is required to anneal and flatten as-rolled titanium plates simultaneously to impart the required product properties. Titanium plates in the hot-rolled condition were used as creep test materials, and the holding operation for 24±4 h to be performed before the start of the test as specified in the JIS and other applicable standards was eliminated. Steady-state creep cannot be identified until tertiary creep is observed. Since this creep test was not conducted to investigate long-term creep properties, it was discontinued after the maximum time of 900 h. Round bar specimens were machined from the thickness center of 11- to 32-mm thick, as-hot-rolled plates of JIS Grades 1, 2 or 3 commercially pure titanium or Ti-6Al-4V alloy in the direction parallel to the rolling direction and were subjected to the creep strain test.

(2) Estimation of strain and strain rate evolving during flattening

The deflection of titanium plates before flattening is usually about 35 mm/1,000 mm and 13 mm/1,000 mm for the thickness ranges of 3.7 to 6.2 mm and of 22 to 37 mm, respectively. The strain ε required to remove this degree of deflection from the titanium plate is estimated to be only about 1.9×10^{-3} in the plate surface. The creep strain introduced by the VCF operation is extremely small as compared with conventional creep rupture strain and is not large enough to damage the material in any way. If this strain is applied for 10 h, the average strain rate during the VCF operation is 5.3×10^{-8} s^{-1}.

(3) Determination of applied stress during creep strain test

When the uniformly distributed load q is applied, the stress at the position z in the thickness direction is given by Eq. (9). The maximum stress in the plate surface can be calculated by substituting a half of the plate thickness into z.

$$\sigma=\frac{M}{In}(Z)^{\left(\frac{1}{n}\right)},\quad In=2\int_0^{\frac{h}{2}} Z^{\left(1+\frac{1}{n}\right)}dz \qquad \cdots\cdots(9)$$

Considering the case where JIS Grade 1 commercially pure titanium plates (length L of 0. 2 to 2 m and thickness h of 5 to 50 mm) are treated at the uniformly distributed load q of 0.096 MPa·m (equivalent to the furnace vacuum of 40 mmHg) and at the temperature of 620°C, the maximum surface stress $\sigma_{x\max}$ is estimated to range from 0.9 MPa to about 8,700 MPa by calculation using Eq. (9). The applied stress was set at especially low levels of 4.9, 9.8, 19.6, 39.2, and 78.4 MPa to evaluate the straightening capacity of the VCF equipment for short (small L) and thick titanium plates.

Table 2 shows the material constants n and A for 10-h quasi steady-state creep as empirical equations by taking the temperature as a function.

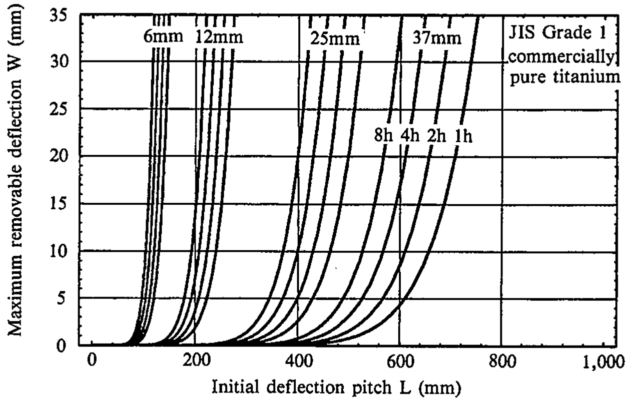
3.3 Estimation of straightening capacity

The deflection W of JIS Grade 1 commercially pure titanium and Ti-6Al-4V alloy plates, 6, 12, 25, or 37 mm thick and having an initial deflection pitch of 0 to 1,000 mm, that can be removed by the VCF treatment was calculated for the furnace vacuum of 40 mmHg, treating temperature of 620°C (JIS Grade 1 commercially pure titanium) or 760°C (Ti-6Al-4V alloy), and treating time of 1, 2, 4 or 8 h. The results are as shown in **Fig. 4**. In the figure, the initial deflection pitch is plotted along the horizontal axis against the removable deflection W along the vertical axis. Space on the right-hand side of each curve indicates the flattening possibility. Take a 37-mm thick JIS Grade 1 commercially pure titanium plate for example. When the treating time is 1 h, the plate with initial deflection height W of 18 mm can be completely flattened if the initial deflection pitch L is equal to or more than 700 mm. When the treating time is increased to 8 h, the plate with the same deflection height and with deflection pitch of about 560 mm or more can be completely flattened. When the plate is of JIS Grade 1 commercially pure titanium, 6 mm in thickness and 35 mm in deflection height, deflections pitched at more than about 120 mm can be removed if the treating time is 8 h.

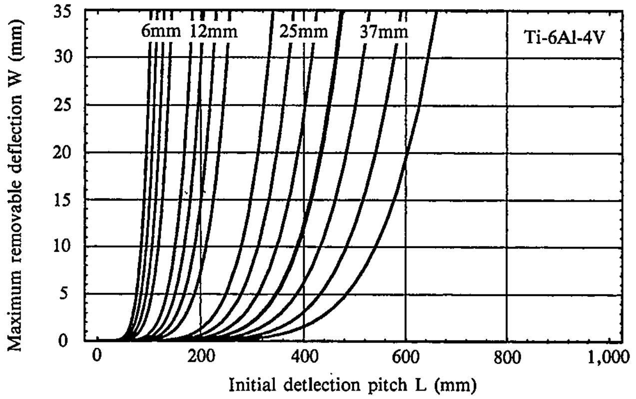
The permissible deflection pitch of the titanium plates shown in **Fig. 4** is much smaller than that of as-hot-rolled titanium plates produced at Nippon Steel's stainless steel plate mill. This means that the VCF equipment can almost completely flatten commercially pure titanium and Ti-6Al-4V alloy plates if the treating temperature and time are correctly set on the basis of the relevant creep data.

Table 2 Material constants of test plates (10-h quasi steady-state creep)

Grade	n	logA [$s^{-1}MPa^{-n}$]
JIS Grade 1 commercially pure titanium	10.57 − 6,127(1/T)	−2.265 − 7,000(1/T)
JIS Grade 2 commercially pure titanium	14.60 − 10,230(1/T)	−7.813 − 1,325(1/T)
JIS Grade 3 commercially pure titanium	12.75 − 8,635(1/T)	−5.399 − 3,781(1/T)
Ti-6Al-4V alloy	5.798 − 3,814(1/T)	−1.565 − 6,483(1/T)



(a) Maximum removable deflection of JIS Grade 1 commercially pure titanium plates (calculated)
Plate thickness: 6, 12, 25, 37 mm, Furnace vacuum: 40 mmHg, VCF treating temperature: 620°C, Treating time: 1, 2, 4, 8 h



(b) Maximum removable deflection of Ti-6Al-4V alloy plates (calculated)
Plate thickness: 6, 12, 25, 37 mm, Furnace vacuum: 40 mmHg, VCF treating temperature: 760°C, Treating time: 1, 2, 4, 8 h

Fig. 4 Calculated Maximum removable deflection

The results obtained here are only the calculated values of deflection at the center of flat plates simply supported at both edges, and therefore may risk an overestimation of the flattening capacity of the VCF equipment. In this connection, there are many reports on the FEM analysis of the bulging deformation behavior of continuously cast slabs taken as the creep deformation of a plates[6-9]. Accurately speaking, a model whereby a curved plate deforms with time and its support points move outward, or a moving boundary model, should be used to make calculations concerning the VCF operation. Such a model, including FEM analysis, will be studied in the future.

4. Material Quality Control in VCF Operation

The preceding chapter has indicated that the VCF equipment can remove almost all normally conceivable deflections from a titanium plate if the titanium plate is treated at the annealing temperature for 8 h. Considering its actual operating performance, the VCF equipment takes a long treating time per batch. Therefore, it sometimes becomes necessary for the VCF equipment to treat different grades or sizes of titanium plates in the same batch. From the point of view of quality design, it is of utmost importance to grasp the quality changes (mechanical properties and microstructure) of titanium plates when annealed at different temperatures for different lengths of time. JIS Grades 1 to 3 commercially pure titanium and Ti-6Al-4V alloy plates were rolled to thicknesses of 21, 14, 13, and 10 mm on a plate mill, soaked in argon or air in an experimental electric furnace at 600 to 710°C for 20 min to 24 h for the commercially pure titanium plates and at 730 to 800°C for 1 to 24 h for the Ti-6Al-4V alloy plates, respectively, and were cooled in the furnace.

They were subjected to room temperature tensile tests as specified in the applicable JIS and AMS standards, and their mechanical properties were analyzed using the Larson-Miller parameter T(20 + log t), where T is heat treating temperature (K) and t is soaking time (h). **Figs. 5** and **6** show the relationship between the tensile strength and the Larson-Miller parameter and that between the tensile elongation and the Larson-Miller parameter, respectively (specimens sampled in the transverse direction). As the Larson-Miller parameter increases, the 0.2% offset yield strength and tensile strength mildly decrease linearly, while the elongation improves. The relationship between the strength and the Larson-Miller parameter can be explained by the Hall-Petch relation because the grain size increases with increasing Larson-Miller parameter. The strength and ductility both fully satisfy the values specified in JIS and AMS. In the VCF operation as stated above, quality design can be accurately made involving the strength and ductility of titanium plates, through the use of the Larson-Miller parameter.

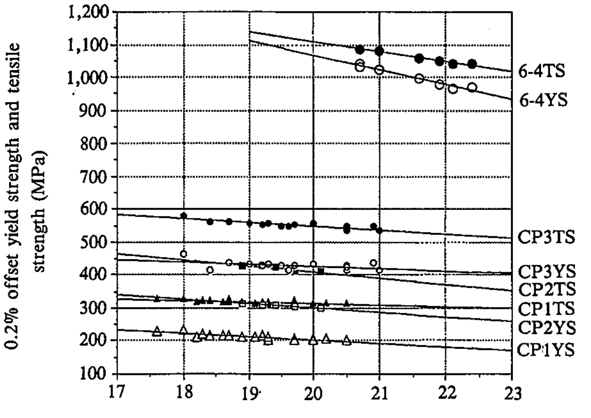


Fig. 5 Larson-Miller parameter plot of tensile strength

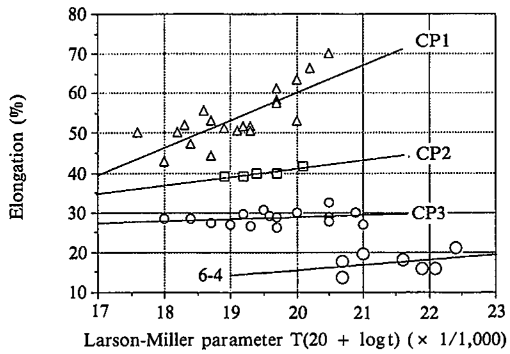


Fig. 6 Larson-Millar parameter plot of elongation

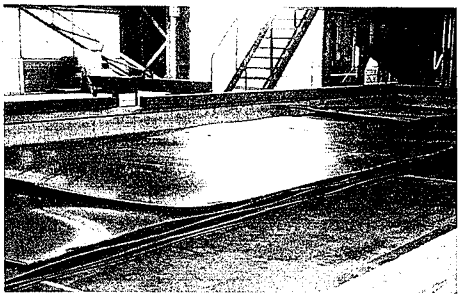
5. Flatness and Mechanical Properties of Titanium Plates Treated on VCF Equipment

The VCF treating conditions (temperature and soaking time) were determined from the creep flattening conditions and heat treating conditions discussed in **Chapters 3** and **4**, and the VCF equipment was actually operated under the conditions thus established. The resultant flatness and mechanical properties of titanium plates are described below.

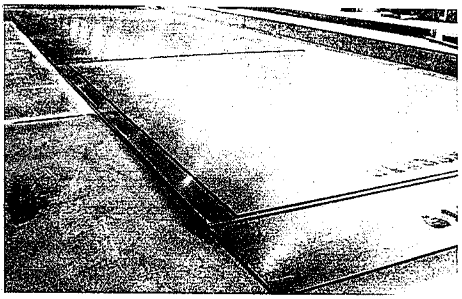
5.1 Flatness

Photo 2 shows the shapes of commercially pure titanium plates before and after the VCF treatment. The changes in the flatness of commercially pure titanium plates after the VCF treatment are shown in **Fig. 7**. The flattening effect was somewhat low for heavy-gage plates, but the target flatness level of 1 mm/m or less was satisfied, and it became possible to produce heavy plates of commercially pure titanium with very good flatness. It was confirmed that the VCF equipment have a similar flattening effect for titanium alloys such as Ti-6Al-4V.

The VCF equipment made it possible to produce titanium plates to very severe flatness specifications (for electrodes, for instance) and light-gage wide titanium plates which Nippon Steel previously considered difficult to make because of the flatness problem. The manufacturable range of titanium plates at Nippon Steel was thus significantly expanded. This excellent flatness performance was due mainly to two factors: (1) The platen surface was finished flat to 0.5 mm/m or less throughout by adopting a new method when the VCF equipment was built; and (2) Optimum flattening and heat treating conditions were established, and operating standards were set to prevent temperature deviations in the width and length directions at the platen surface.

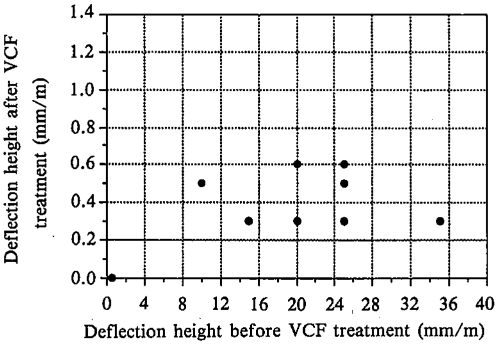


(a) Shape of plates before VCF treatment

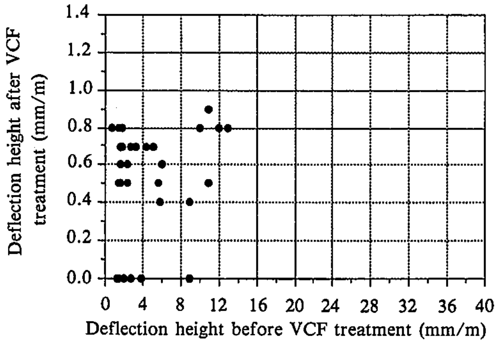


(b)Shape of plates after VCF treatment

Photo 2 Shape of hot-rolled commercially pure titanium plates before and after VCF treatment



(a) Light-gage JIS Grade 1 and 2 commercially pure titanium plates
Plate thickness: 3.7 - 6.2 mm, Plate width: 1,200 - 3,200 mm, Treating temperature: 590 - 650°C, Soaking time: 5 h



(b) Heavy-gage JIS Grade 1 and 2 commercially pure titanium plates
Plate thickness: 22 - 37 mm, Plate width: 1,300 - 2,200 mm, Treating temperature: 600 - 650°C, Soaking time: 5 h

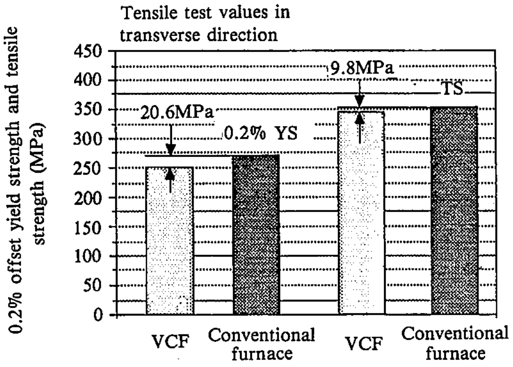
Fig. 7 Straightening effect of VCF treatment

5.2 Mechanical properties

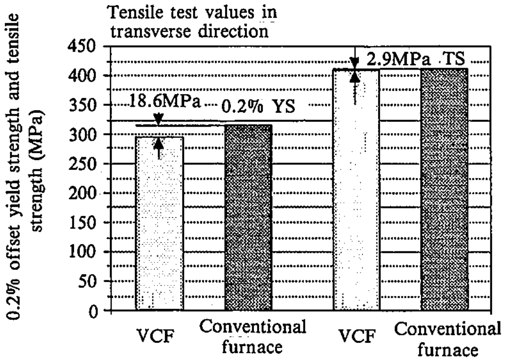
In **Fig. 8**, hot-rolled plates of JIS Grade 1 and 2 commercially pure titanium treated in the VCF equipment are compared in mechanical properties with the same plates treated in a conventional heat treating furnace. As shown, the former fully satisfies the specified values as expected. The 0.2% offset yield strength of the VCF treated plates are about 20 MPa lower than those of the plates heat-treated in the conventional furnace. This is because the latter was finally cold leveled to undergo slight work hardening.

6. Conclusions

Outline descriptions have been made of the vacuum creep flattening (VCF) equipment installed at the stainless steel plate mill of Yawata Works for flattening titanium plates, estimation of the straightening capacity, control of mechanical properties and microstructures and the flatness and mechanical properties of titanium plates treated on the VCF equipment. Coupled with a wide belt polisher and all-surface marker installed at the same time, the VCF equipment significantly expanded the available size range of titanium plates at Nippon Steel. Titanium plates to severe flatness specifications (for electrodes, for instance) and wide light-gage titanium plates have been added to the company's titanium product line. The authors intend to continue on the development of new products and processes to meet the new needs of customers.



(a) JIS Grade 1 commercially pure titanium plate
Plate thickness: 5 - 7 mm, Composition: O = 0.058%, Fe = 0.036%, VCF furnace: 600°C × 5 h, Conventional furnace: 670°C × 20 min



(b) JIS Grade 2 commercially pure titanium plates
Plate thickness: 4 mm, Composition: O = 0.082%, Fe = 0.045%, VCF furnace: 650°C × 5 h, Conventional furnace: 710°C × 20 min

Fig. 8 0.2% offset yield strength (YS) and tensile strength (TS) of commercially pure titanium plates heat-treated in VCF equipment and conventional furnace

Acknowledgment

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References

1) Mach Tool Blue Book. October 1971, 66, 61
2) Metals Handbook. Ninth Edition. Vol. 4, ASM, 1981, p.763
3) Poirier, J.P.: Creep of Crystals. Cambridge University Press, 1985, p.27
4) Inoue, T.: Kyoto University, Private communication, May 20, 1991
5) Odqvist, F.K.G., Hult, J.: Kriechfestigkeit metallischer werkstoffe. Springer-Verlag, 1962, Japanese translation, Baifukan, 1967, p.135
6) Miyazawa, K., Schwerdtfeger, K.; Ironmaking and Steelmaking. 68 (1979)
7) Matsumiya, T., Kajioka, H., Nakamura, Y.: Seitetsu Kenkyu. (310), 402 (1982)
8) Fukawa, K., Matsumoto, H., Nakajima, K.: Tetsu-to-Hagané, 68, 794 (1982)
9) Yoshii, A., Kihara, S.: Proc. ICM-5. Vol. II, 1987, p.1123