

Development of a Manufacturing Process for High Strength Ti-Al-Fe-Mo Titanium Alloy Large Diameter, Heavy Wall Thickness Welded Pipes

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Abstract

In geothermal power generation which is one of the clean renewable energies without serious CO₂ emission, materials having both high strength at relatively high temperature and high corrosion resistance are used for casing pipes. For such use, the manufacturing process of large diameter - heavy wall thickness welded pipe of high strength titanium alloy were developed. Alloy compositions were examined by adjusting that of a high strength titanium alloy, Super-TIXTM 523AFM (Ti-5Al-2Fe-3Mo). As a result of the study, two alloy compositions were selected: Ti-5Al-1Fe-3Mo(-0.13O) and Ti-5Al-2Fe-1.5Mo(-0.13O). After confirming that the materials have the expected level of mechanical properties, weldability and corrosion resistance, etc. by the laboratory examinations, plates of 17 mm thick, 2400 mm wide and 6 m long were manufactured from 1.8 ton VAR ingots in an actual plate manufacturing mill (Nippon Steel & Sumikin Stainless Steel Corporation Yawata Works). Furthermore, welded pipes of 17 mmWT, 360 mmOD, 1 m long were manufactured by press bending and high-efficiency welding process. It was confirmed that the mechanical properties of both base and welded metals are fully competitive to Ti-6Al-4V ELI and the pipes have good tolerance and no serious defects in the weld metals.

1. Introduction

Geothermal power is a low CO₂ emission source of sustainable clean energy, similar in that sense to solar (photovoltaic / heat) and wind power. It is of significant value, and its power generation capability is stable. In geothermal power generation, in some cases high strength, high corrosion-resistant stainless steel and titanium alloys are used for casing pipes in wells that pump up hot water and high temperature, high pressure steam which, depending on the circumstances, may also be highly corrosive. Furthermore, for riser pipes for submarine oil and gas fields, which today go far deeper under the sea, titanium alloys having high strength, light weight, low Young's modulus, and high corrosion resistance properties are ap-

propriate, and there are indeed reports of such applications.¹⁾

For such uses, Ti-6Al-4V ELI (+Pd/Ru) (ELI: Extra Low Interstitials) is mainly used, although to expand application further it is necessary to develop a lower cost, higher strength titanium alloy. For example, Ti-5Al-1Fe (Super-TIXTM 51AF) and Ti-5Al-2Fe-3Mo (Super-TIXTM 523AFM) have been developed utilizing inexpensive Fe.²⁻¹³⁾ Pipes for this kind of use generally have a heavy wall thickness and large diameter. In order to easily develop such pipes in the near future for the exploration of new energy resources, it is necessary to use a technology that permits the efficient production of heavy wall thickness, large diameter pipes made from a high strength titanium alloy.

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This article reports on the development of such a technology for producing heavy wall thickness, large diameter welded pipes, using high strength titanium alloy plates. During this development, pipe formation involving a bending plate + welding process was employed, in which rolled plates with excellent thickness accuracy were bent to pipe form, after which the edges were butt-welded. For this process, a study was made to design alloy compositions of titanium alloy and a texture controlled during plate rolling. The plates were produced using an actual heavy plate rolling mill. Controlling the texture is important to ensure press-bending formability. Next, heavy wall thickness, large diameter welded pipes were produced, utilizing the press-bending process and highly efficient keyhole welding by plasma arc.¹⁴⁾ It was confirmed that the welded pipes have satisfactory properties.¹⁵⁾ This article introduces the development of these technologies. The development was financially supported by Japan's Ministry of Economy, Trade and Industry under the project title "Process Technology Development Project for the Creation of High Function Titanium Alloys" (2005-2008).

2. Designing Alloy Compositions

The design composition of titanium alloy plates assumed the plates' target use to be geothermal casing pipes for geothermal power generation, and aimed for efficient development. To ensure strength and ductility, the composition study focused on Ti-5Al-2Fe-3Mo (Super-TIXTM 523AFM),²⁻¹³⁾ which is known as a high strength, high ductility $\alpha+\beta$ type titanium alloy.

Next, six 200kg ingots, each having a different composition selected from a range of Ti-5Al-(1-2)Fe-(1.5-4)Mo-(0.08-0.18)O, were produced by the VAR (Vacuum Arc Remelting) process. After forging, plates with a thickness of 12mm were produced by simplified cross-rolling, where the rolling direction was changed 90 deg. by turning in the second half of the rolling stage, after which $\alpha+\beta$ annealing (750°C, 1 h, air cooling) or β annealing (1,000°C, 10 min, air cooling + 750°C, 2 h, air cooling) was applied. From these materials, round bar type test specimens for tensile strength tests (6.25mm in diameter at the parallel section, 25mm gauge length, ASTM E8 half size) and Charpy impact test specimens (JIS Z 2201, 2mm V-notched in thickness direction) were taken in the direction parallel to the direction of rolling in the final stage (L-direction) and traverse direction (T-direction). Tensile tests and Charpy impact tests were carried out at room temperature.

In all five 200kg-VAR-processed materials that excluded Ti-5Al-1Fe-1.5Mo-0.18O, $\alpha+\beta$ annealed materials exhibited tensile strengths higher than 1,000MPa and elongation higher than 15%, while β annealed materials exhibited tensile strengths higher than 950MPa and elongation higher than 7%. Charpy impact absorption energy higher than 20J was obtained in β annealed materials of the four grades that excluded Ti-5Al-2Fe-4Mo-0.18O and Ti-5Al-2Fe-3Mo-0.17O.

Based on a comprehensive assessment of the above, two grades of Ti-5Al-1Fe-3Mo-0.13O and Ti-5Al-2Fe-1.5Mo-0.13O were selected, due to their correlations balanced among strength, ductility and toughness, and due also to their lower amount of alloy addition. Trial production of these alloys was conducted using actual production equipment, as stated in Section 4.3. In order to enhance fracture toughness, the targeted oxygen value was set at 0.13 mass%, slightly lower than the approximately 0.15 mass% of general high strength $\alpha+\beta$ type alloys.

3. Corrosion Resistance of the Ti-Al-Fe-Mo (-Pd) Alloy

The service environment for geothermal casing pipes is high temperature and high pressure. In addition, depending on the geography, the pipes may be exposed to fluids containing highly corrosive substances (H^+ , Cl^- , SO_4^{2-} and the like). The chemical composition of the fluids varies greatly, depending on the geothermal field. As an example of such environments, an assessment was carried out on the effect of alloying elements on crevice corrosion resistance in a boiling salt solution (pH value adjusted by HCl) in a crevice-corrosion-developing region with a pH less than 1, using Ti-5Al-2Fe-3Mo and another material that included the addition of a small amount of Pd. The materials catered for the test were Ti-5Al-2Fe-3Mo-(0, 0.05, 0.10, 0.20) Pd. The tests were based on ASTM G78 for multiple crevices.

The multi-crevice corrosion test for 350h in a boiling 20% NaCl solution with pH 0.5 indicated no obvious weight reduction due to corrosion—rather, a very slight increase in weight was observed in all test specimens. Under these test conditions, the test specimen that exhibited clearly identifiable crevice corrosion was only the Ti-5Al-2Fe-3Mo without alloyed Pd. When Pd was added by more than 0.05%, the generation of crevice corrosion was not detected. Specifically, it was confirmed that, similarly for pure titanium and general titanium alloys, the addition of a small amount of Pd to the Ti-Al-Fe-Mo titanium alloys is effective in enhancing crevice corrosion resistance.

4. Technology for the Production of High Strength Titanium Alloy Plates

4.1 Study of plate rolling method

For the production of long casing pipes using the press-bending method, a texture is required for the material plate, to take advantage of the bending of long plates in the width direction (T-bending). Generally, when an $\alpha+\beta$ alloy is heated up to the single β phase region or the $\alpha+\beta$ two phase high temperature region and rolled in one direction, T-texture appears, in which the $\langle 0001 \rangle$ direction of hcp, a crystalline structure of α phase, is oriented in the width direction. In this case, ductility in the T-direction, or bending direction, becomes lower, disadvantaging the bending work. Therefore, improvement in the texture by cross-rolling was studied.

Since hot deformation resistance of high strength titanium alloy is high, rolling of long and wide plates in the $\alpha+\beta$ two phase region is difficult even using a powerful heavy steel plate rolling mill. Then, heating to single β phase, which provides a lower deformation resistance, was selected. In this case, since an acicular structure with poor ductility and strong T-texture tends to develop easily, "One heat simplified cross-rolling" was adopted, in which rolling in the cross direction during the latter stage of rolling at a dual phase temperature region is conducted. This process helped obtain a mill-annealed microstructure with excellent ductility, and also ensure ductility in the T-direction by reducing T-texture.

4.2 Laboratory rolling simulating actual rolling

Slabs of Ti-5Al-1Fe-3Mo-0.16O and Ti-5Al-2Fe-1.5Mo-0.16O made from 200kg ingots were heated up to the 1,050°C single β phase region and rolled from 100mm thickness to 60mm thickness. Then the rolled materials were reheated to up to 900°C $\alpha+\beta$ dual phase region and rolled from 60mm thickness to 12mm thickness in the direction perpendicular to the direction of rolling in former rolling, and thus, two-heat rolling simulating "One-heat simplified cross-rolling" was conducted. After annealing at 750°C for one hour

and air cooling, sectional microstructures were observed. Tensile tests were conducted at room temperature using the method described in chapter 2. **Photo 1** shows sectional microstructures, while **Fig. 1** shows tensile properties. Both of the plates exhibited a 0.2% proof stress higher than 860 MPa, a tensile strength higher than 960 MPa, an elongation higher than 18%, and a strength/ductility ratio equivalent to or better than that of annealed Ti-6Al-4V ELI material. Elongation in the T-direction, the direction of bending in pipe forming, was also high.

4.3 Plate production using an actual plate rolling mill

1.8 ton and 720 mm-diameter ingots of Ti-5Al-1Fe-3Mo-0.13O and Ti-5Al-2Fe-1.5Mo-0.13O subjected to plate production were prepared by the double VAR process. After heating to β region and forging, the slab surface was machine-cut. Defects and/or cracks that could cause qualitative defects were not found. Later, the materials were rolled in the Heavy Plate Mill in Yawata Works of Nippon Steel & Sumitomo Metal Corporation.

For the plate rolling, the materials were heated up to 1,050°C single β phase, and then the first stage of rolling was performed. The second stage of rolling in the cross direction was carried out after confirming that the plate surface temperature dropped to the $\alpha+\beta$ two phase region of below 910°C. In this way, plates about 17 mm

in thickness, 2,400 mm in width and 6 m in length were produced (see **Photo 2**).

4.4 Material properties of plates produced using an actual plate rolling mill

The microstructures of plates produced using an actual plate rolling mill, then annealed for 4 h at 720°C and then air-cooled (**Photo 3**), exhibited primarily an acicular structure unlike the structures of laboratory base test specimens shown in Photo 1. This is attributed to the fact that the inside temperature of the material rolled was slightly higher, and the fact that cross-rolling was applied while the material was still partially untransformed. Tensile tests and fracture toughness tests (J_{IC}) were conducted on test specimens sampled from plates actually produced using the rolling mill, and subjected to $\alpha+\beta$ annealing (720°C, 4 h, air cooling) and β annealing (1,000°C, ten minutes, air cooling). Round bar tensile test specimens (diameter 12.5 mm in the parallel section, gauge length 50 mm, ASTM E8) were taken in the direction parallel to the direction of rolling at the final stage (L-direction) and in the direction perpendicular to the L-direction (T-direction).

During room temperature tensile testing, stress was controlled to 15 MPa/s until a 0.2% proof stress was determined, and then stroke was controlled to 20 mm/min. The side-grooved 1/2 CT test specimens shown in **Fig. 2** (fracture toughness test) were taken in such a way that the fracture propagation direction was parallel to the direction of rolling and perpendicular to that direction, and fatigue pre-cracking ($a_0/W \approx 0.55 - 0.60$) was introduced. Fracture toughness tests were conducted using the unloading elastic compliance method according to ASTM E1820. Here, actual measured values of 0.2%

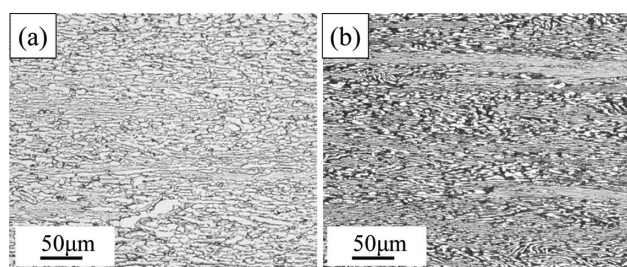


Photo 1 Microstructures of the longitudinal section of the annealed plates which were rolled in the laboratory condition as the simulation of actual process
(a) Ti-5Al-2Fe-1.5Mo, (b) Ti-5Al-1Fe-3Mo

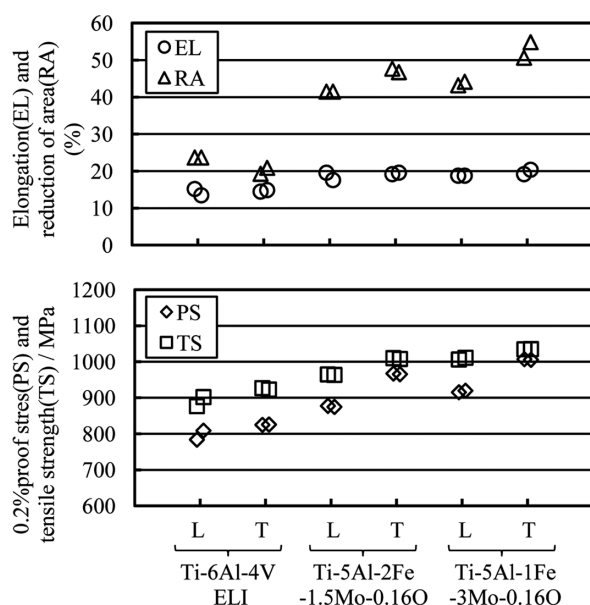


Fig. 1 Tensile properties of the annealed plates which were rolled in the laboratory condition as the simulation of actual process



Photo 2 Appearance of Ti-5Al-2Fe-1.5Mo-0.13O plate of 17 mm thick, 2,400 mm wide, 6 m long rolled at actual heavy plate mill

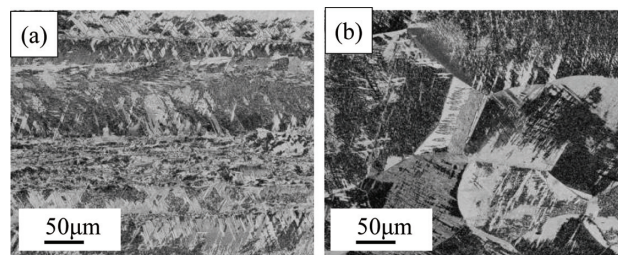


Photo 3 Microstructures of the longitudinal section of the Ti-5Al-2Fe-1.5Mo plate rolled at actual mill
(a) $\alpha+\beta$ annealed, (b) β annealed

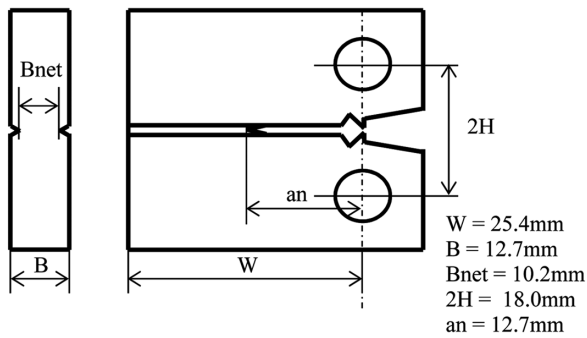


Fig. 2 Dimensions of the compact tension specimen for the fracture toughness test

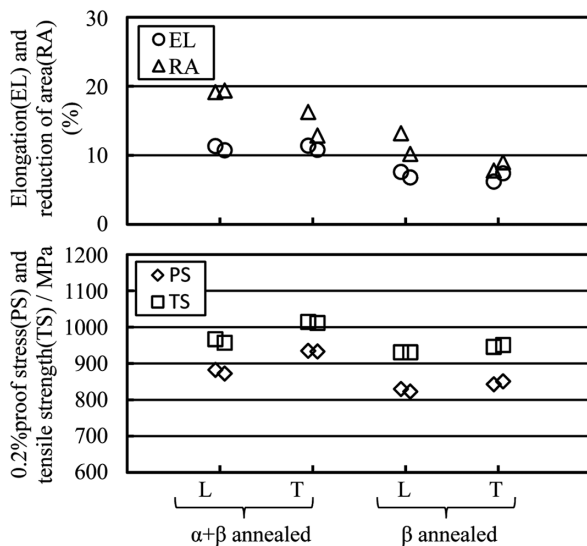


Fig. 3 Tensile properties of the Ti-5Al-2Fe-1.5Mo-0.13O plate rolled at actual mill

proof stress and tensile strength of alloys were used, and a fixed value of Poisson's ratio of 0.3 and a fixed value of Young's modulus of 118 GPa were used. Fracture toughness values were arranged with respect to $K(J_Q)$ values converted from J_Q values.

Figure 3 shows tensile test results. Strength in T-direction is slightly higher, and elongation in T-direction is accordingly slightly lower. Since the plate temperature at the time of rolling was slightly higher and the acicular structure remains, elongation was lower than in the laboratory test specimen taken from the 200 kg material. However, an elongation higher than 10% was obtained in the $\alpha+\beta$ annealed material. Figure 4 shows fracture toughness test results. Values judged as "Invalid" according to ASTM judging criteria are denoted with an * in the graph. In the materials, $K(J_Q)$ values converted from J_Q values of $\alpha+\beta$ annealed material are 56–68 $\text{MPa}\cdot\text{m}^{1/2}$, and 75–78 $\text{MPa}\cdot\text{m}^{1/2}$ in the case of β annealed material, both being equivalent to those of Ti-6Al-4V-ELI and the like.

5. Press-bending Pipe Forming Technology

5.1 Study of pipe forming methods

Two pipe forming methods were studied: seamless pipe forming (piercing method, hot extrusion method and the like), and welding pipe forming (UOE, spiral forming, press forming and the like). The focus of attention for the press-bending method is: (1) a high poten-

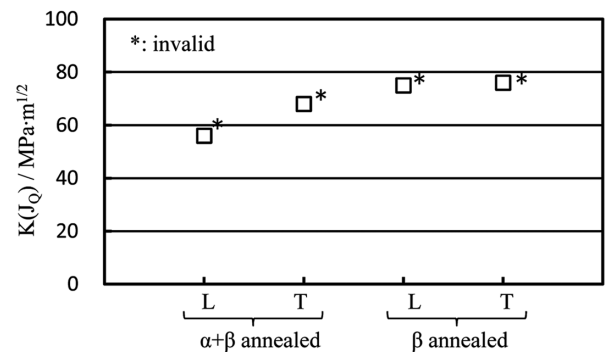


Fig. 4 Fracture toughness of the Ti-5Al-2Fe-1.5Mo-0.13O plate rolled at actual mill

tial for production of heavy wall thickness, large diameter pipes; (2) a high readiness for small-lot production of pipes with various wall thicknesses, sizes and material types; and (3) a high availability of existing pipe-production equipment and therefore relatively low investment cost. Disadvantageous aspects of the press-bending method are: (1) welding is necessary; and (2) ensuring high circularity accuracy is relatively difficult. As for the welding requirement in (1), keyhole welding by plasma arc, which has a successful history of application to welding thick titanium alloy materials, can achieve efficient welding.¹⁴⁾ And with regard to ensuring circularity accuracy ((2)), improvement in circularity is possible during the subsequent process of heat treatment after press-forming (explanation omitted in this report).

5.2 Study on forming by simulation

A study was carried out using an FEM forming simulation model to identify the most appropriate pressing method for press-bending forming of a titanium alloy.¹⁶⁾ In press-bending forming, issues requiring resolution include improvement in edge-butting accuracy, camber prevention in the axial direction of a pipe caused by spring back, and polygonal development in the pipe section. Pressurized bending was shown to be effective in alleviating the influence of spring back. Die design that produces the desired radius curvature without pressurizing was also studied. For further information, refer to reference literature.¹⁶⁾

5.3 Press-bending pipe forming of plates using an actual machine

Press-bending pipe forming of titanium alloy plates was carried out at Nishimura Koki Co., Ltd., using the pipe forming method for carbon steel that pays attention to specific phenomena that appear during titanium formation, such as spring back.

The targeted pipe dimensions were 17 mm wall thickness and 360 mm outer diameter. This is the dimension of geothermal casing pipes currently used. First, a short pipe 1 m in length was produced for trial purpose, followed by mid length pipes of 2 m. The materials were taken from actually produced plates of Ti-5Al-2Fe-1.5Mo-0.13O and Ti-5Al-1Fe-3Mo-0.13O, then annealed, shot-blasted, pickled and ground, with the edges cut to form I-shaped grooves in welding.

Press-bending forming was carried out, heating plates with burners to 200–350°C before press-forming as a safety precaution. Because the elongation in the T-direction in actually produced plates was slightly low. Pipes of one meter and two meters in length with wall thickness of 17 mm and outer diameter of 360 mm were produced. The forming temperature was determined according to the results of previously conducted warm state tensile tests. The gap be-

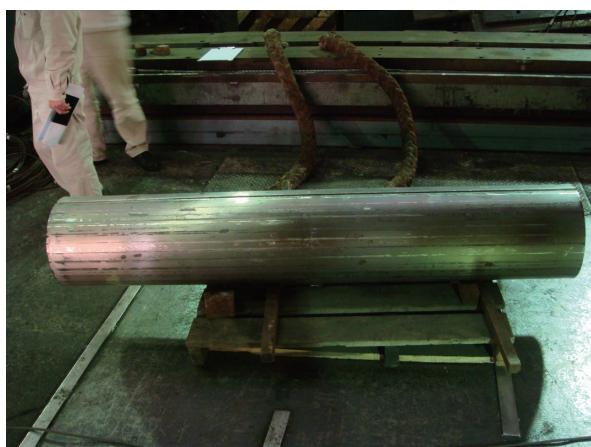


Photo 4 Appearance of the 17 mmWT, 360 mmOD, 2 m long pipe formed by press bending

tween edges after forming was sufficiently small and satisfactory shapes were obtained. **Photo 4** shows an external view of the plate after press-bending forming.

6. Welding and Assessment of a Welded Pipe Produced for Trial Purposes

6.1 Welding method

TIG welding is generally used for welding titanium material. However, when welding a thick material, a V-shaped groove with a large section area is needed, and multi-layered welding with filler wire is also required. In this case, TIG welding (which characteristically has a low speed) for multi-layered welding causes problems, such as prolonged welding time, a notable deterioration in productivity, and considerable strain due to the welding. Therefore, this development employed one pass butt-welding for I-shaped grooves, with highly efficient keyhole welding by plasma arc,¹⁴⁾ which has a history of application for 20 mm thickness $\alpha+\beta$ type titanium alloy with success in one pass welding.

The study of welding conditions examined pieces of sheet taken from an actually produced plate, each measuring 17 mm in thickness, 140 mm in width and 280 mm in length, with edges machined for grooves. By optimizing conditions such as current, chip diameter, gas flow rate and shieldability, excellent butt-welded joints were obtained at a welding speed of 1.4×10^{-3} m/s. Under these conditions, butt-welding was applied to the material pipe with a length of 1,000 mm, as explained in Chapter 5. **Photo 5** shows an external view of the pipe after welding.

6.2 Assessment of welded pipe produced for trial

After welding, the pipe was annealed for 4h at 720°C or for 1h at 800°C and air-cooled. Then tensile characteristics and fracture toughness were assessed. Test specimens were taken at the weld section and at the position opposite to the weld in the circular direction. The direction of crack propagation in the specimens was parallel to the longitudinal direction of pipes. Tensile tests used the round bar test specimens described in Chapter 2. Fracture toughness tests used the 1/2T CT test specimens shown in Fig. 2. Test results were arranged with respect to $K(J_Q)$ values converted from J_Q values in the manner described in Section 4.4.

Figure 5 shows the test results for Ti-5Al-2Fe-1.5Mo-0.13O after annealing at 800°C for 1h. Both the base material and the weld material exhibited a 0.2% proof stress higher than 860 MPa, a ten-

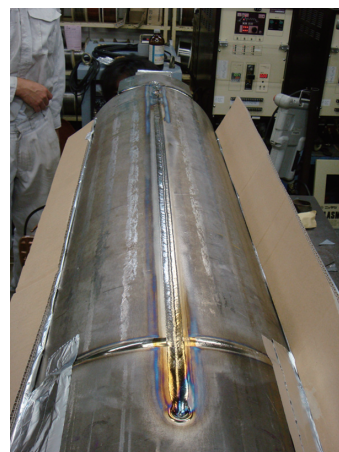


Photo 5 Appearance of the 17 mmWT, 360 mmOD, 1m long welded pipe

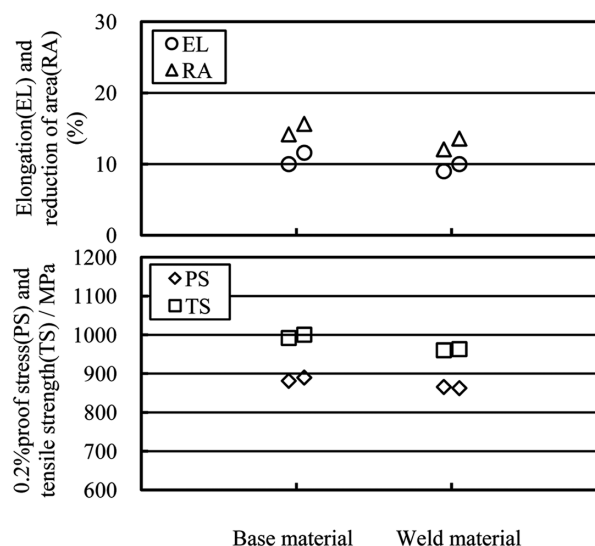


Fig. 5 Circumferential tensile properties of the welded pipe of Ti-5Al-2Fe-1.5Mo-0.13O

sile strength higher than 960 MPa, an elongation higher than 9%, and a strength higher than that of Ti-6Al-4V ELI. **Figure 6** shows the results of the fracture toughness tests. For $K(J_Q)$ values converted from J_Q values, $\alpha+\beta$ annealed material (720°C, 1h) of Ti-5Al-2Fe-1.5Mo-0.13O exhibited the value $64 \text{ MPa} \cdot \text{m}^{1/2}$, the annealed material Ti-5Al-1Fe-3Mo-0.13O exhibited values higher than $72 \text{ MPa} \cdot \text{m}^{1/2}$, and the β annealed materials of both alloys exhibited sufficient values above $72 \text{ MPa} \cdot \text{m}^{1/2}$.

7. Conclusions

As stated above, plate production technology for high strength Ti-Al-Fe-Mo titanium alloy and production technology for heavy wall thickness/large diameter pipes were developed. This established the prospect for production of heavy wall thickness/large diameter titanium alloy pipes of 1,000 MPa class $\alpha+\beta$ type by press-bending and welding. Heavy wall thickness, large diameter pipes to be produced by this development can be applied not only to casing pipes for geothermal power generation (geothermal wells), but also to riser pipes used for the development of petroleum, gas, methane hydrate and other energy resources. Utilization of such pipes for an

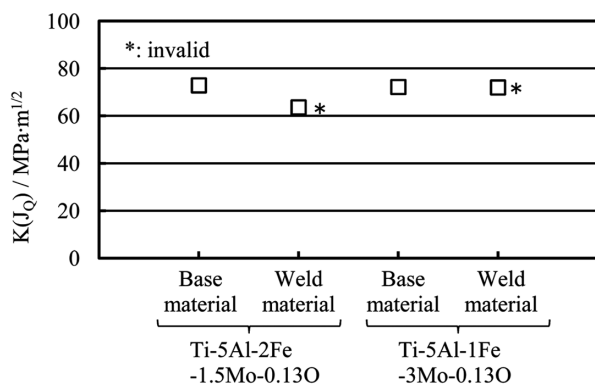


Fig. 6 Fracture toughness of the welded pipe of Ti-5Al-2Fe-1.5Mo-0.13O and Ti-5Al-1Fe-3Mo-0.13O

even wider range of purposes is expected.

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