Technical Report

Applications of Titanium and Its Alloys for Weight Reduction and Enhanced Functionality of Automobiles

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Abstract

Weight reduction and enhanced functionality in automobiles are critical challenges, and titanium is considered a material that can address these issues. However, there are many challenges in applying titanium, and our company has been developing titanium materials with excellent properties and solution technologies. In material development, we have created the "Super-TIX™ series," which utilizes inexpensive, common elements. We have mainly introduced alloys for exhaust systems and high-strength titanium alloys. In terms of solution technologies, we have introduced press forming simulations and lubrication during pressing.

1. Introduction

In automobiles, vehicle weight has increased due to the installation of safety devices, while stricter emission regulations demand weight reduction. Achieving automotive weight reduction requires improving the specific strength of materials. For steel, the development of high-tensile steel has progressed,[1] while multi-material strategies using lightweight metals such as titanium, aluminum, and magnesium, as well as CFRP, is also being pursued.[2]

Titanium has been used for lightweight automotive components since the 1980s, primarily in racing vehicles, for parts such as connecting rods, engine valves, and suspension springs. However, while titanium offers high performance, its high cost has limited its application mainly to racing and luxury cars. To reduce material costs, Nippon Steel Corporation developed the Super-TIX™ series, which replaces expensive alloying elements such as V and Mo traditionally used in general-purpose titanium alloys with less expensive, common elements.[3] These alloys have been applied to automotive components.

Meanwhile, part manufacturing costs account for a larger proportion than material costs, necessitating efforts to reduce them. Nippon Steel has been developing technologies to enable wider titanium application, including materials with improved machinability[4] and press-forming solution technologies that account for titanium's unique anisotropy. This paper introduces some of these initiatives, focusing on the characteristics of the developed materials and solution technologies. For components not covered here, please refer to past articles.[5, 6]

2. Exhaust System Components

Exhaust system components are parts where titanium adoption has progressed for a long time. Titanium has been applied not only for weight reduction but also from a design perspective. Since these components are manufactured by forming sheets, formability is essential. Furthermore, as they are exposed to high-temperature environments, high-temperature mechanical properties and oxidation resistance are also required. Nippon Steel has developed and commercialized the Super-TIX™ series (hereafter referred to as STIX) of alloys, utilizing copper to enhance high-temperature strength while maintaining room-temperature workability (see **Table 1**).[7] The following sections outline key properties of these alloys.

2.1 Temperature dependence of tensile properties

Figure 1 shows the temperature dependence of tensile strength. The tensile direction is perpendicular to the rolling direction (T-direction), and the strain rate is 30%/min at room temperature. For other temperatures, it is 7.5%/min. Results for SUS436 and JIS Grade 2 pure titanium (CP-Ti) are also shown for comparison. Tensile strength decreases with increasing temperature for all materials. Across the entire temperature range, tensile strength is highest in the order: CP-Ti, STIX-10CU, STIX-10CSSN-1, SUS436.

Figure 2 shows the relationship between specific strength (tensile strength/density) and temperature. Density values are those at room temperature, using the values listed in Table 1 and 7.70 g/cm^3 for SUS436. Specific strength (Fig. 2 (a)) is clearly higher for STIX-10CU and STIX-10CSSN-1 from near room temperature up to

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Table 1 Typical chemical composition and properties at room temperature in titanium for exhaust system

Material	Chemical composition (mass%)					Tensile properties				Density (g·cm^{-3})
	Cu	Sn	Si	Nb	O	Heat treatment	0.2%PS (MPa)	TS (MPa)	El (%)	
JIS class 2					≤0.20	Annealing	≥215	≥340	≥23	4.51
10CU[7]	1.0				≤0.15	Annealing	≥270	≥360	≥35	4.54
10CUNB[7]	1.0			0.5	≤0.15	Annealing	≥270	≥360	≥35	4.55
10CSSN-1	1.0	1.0	0.2	0.4	≤0.15	Annealing	≥270	≥395	≥20	4.55

about 500°C. However, they are comparable above 600°C. For a more detailed comparison, Fig. 2 (b) shows the ratio relative to the specific strength of SUS436. CP-Ti is less than 60% of SUS436, while STIX-10CU is about 90%. However, STIX-10CSSN-1, which exhibits the highest high-temperature strength, is about 20–30% higher than SUS436.
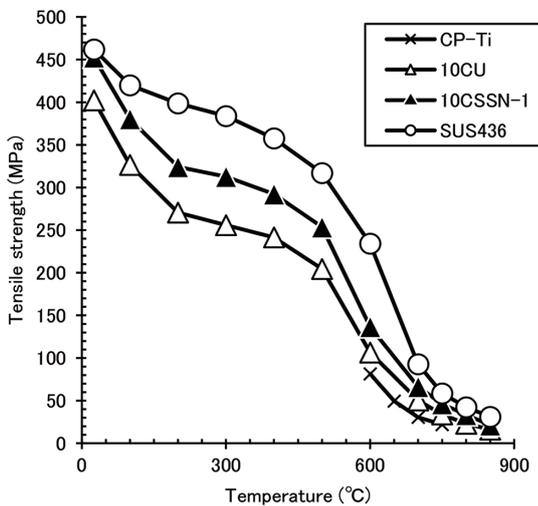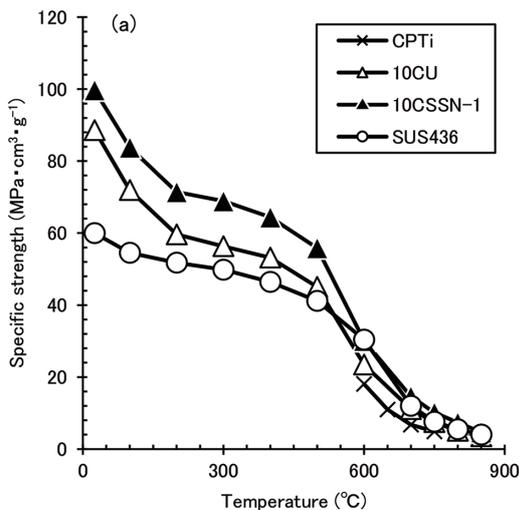

Fig. 1 Relationship between tensile strength and temperature

2.2 Fatigue properties

Figure 3 shows the S-N curves for plane bending fatigue at a stress ratio of −1 at 750°C. Hourglass-shaped specimens were prepared in the T direction, and the specimen surfaces were left as-product. The solid line in the figure represents the curve following the semi-logarithmic curve model. The fatigue strength (Fig. 3 (a)) showed that SUS436 exhibited the highest fatigue strength, similar to high-temperature tensile strength. However, when normalized by density (same as Section 2.1) (Fig. 3 (b)), SUS436 and STIX-10CSSN-1 displayed very similar S-N curves, being nearly equivalent at high cycle counts.

2.3 Oxidation resistance

Titanium oxidizes readily, making oxidation resistance a key challenge. **Figure 4** shows the relationship between oxidation weight gain and temperature during 200 hours of continuous atmospheric oxidation. Compared to SUS436, all titanium materials exhibit oxidation rates one to two orders of magnitude higher, confirming titanium's susceptibility to oxidation. When performance degradation due to oxidation-induced weight loss during use is a concern, heat-resistant titanium alloy sheets containing Al, Si, and Nb are employed. Even for titanium alloys, those lacking these elements, such as STIX-10CU containing only Cu, exhibit oxidation resistance equivalent to pure titanium. Conversely, STIX-10CUNB, which adds Nb to STIX-10CU, shows improved oxidation resistance, and STIX-10CSSN-1, containing both Si and Nb, demonstrates further improvement. At 800°C, STIX-10CSSN-1 and STIX-10CUNB exhibit equivalent performance, attributed to the higher
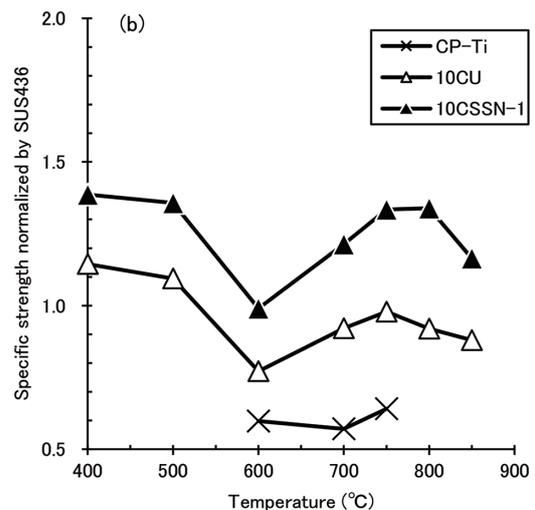

Fig. 2 Specific strength as a function of temperature
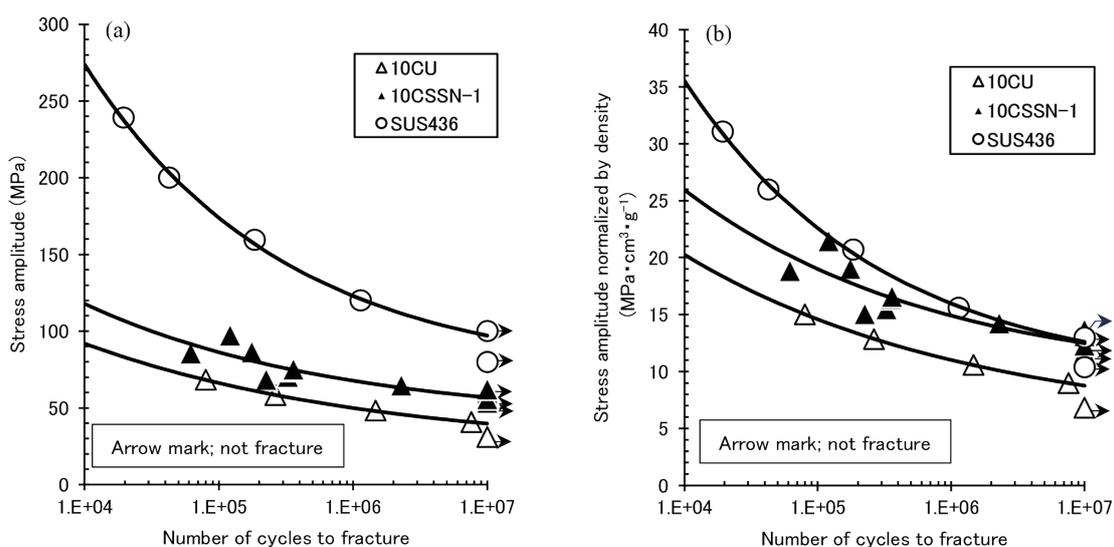**(a) Specific strength of each material and (b) specific strength ratio normalized SUS436.**

Fig. 3 S-N curves at 750°C
(a) Stress amplitude and (b) stress amplitude normalized by density of each material.

Nb content in STIX-10CUNB compared to STIX-10CSSN-1. This indicates that Si addition is more effective than Nb for improving oxidation resistance near 700°C, while Nb becomes more effective at higher temperatures.

While adding larger amounts of elements like Al, Si, or Nb could further enhance oxidation resistance, adding more oxidation-resistant elements beyond this point would lead to reduced cold workability and increased material costs. Therefore, to achieve oxidation resistance exceeding that of STIX-10CSSN-1, applying surface treatment according to the component replacement cycle is more effective.

2.4 High-temperature salt damage resistance

For exhaust system materials, evaluation of high-temperature salt corrosion resistance against deicing agents used for road surface freezing prevention may be required. It has been suggested that the Cu used in Nippon Steel's developed material promotes high-temperature salt corrosion, while Si and Nb suppress it.[8] Furthermore, high-temperature salt corrosion is reported to progress through a cycle of: 1) NaCl vapor reacting with the titanium oxide film to generate Cl gas, 2) Cl gas reacting with base metal elements to form volatile chlorides, and 3) oxidation of the chlorides releasing Cl gas.[9] Therefore, even in alloys containing Cu, adding Nb and Si—elements that suppress atmospheric oxidation—is expected to inhibit chloride oxidation by limiting oxygen supply, thereby ensuring high-temperature salt corrosion resistance.[10]

2.5 Corrosion resistance to condensate

In exhaust system components, residual exhaust gas cools upon engine shutdown, forming water containing exhaust gas constituents. Consequently, water containing these constituents repeatedly forms, condenses, and evaporates with engine start-stop cycles. Therefore, evaluating corrosion resistance under such conditions is also necessary. **Table 2** shows the results of corrosion testing conducted according to JASO-M611-92-A. Pitting depth is equivalent between STIX-10CSSN-1 and SUS436. Furthermore, corrosion weight loss is negligible for SUS436, while STIX-10CSSN-1 showed a slight weight increase after testing. These results demonstrate that titanium
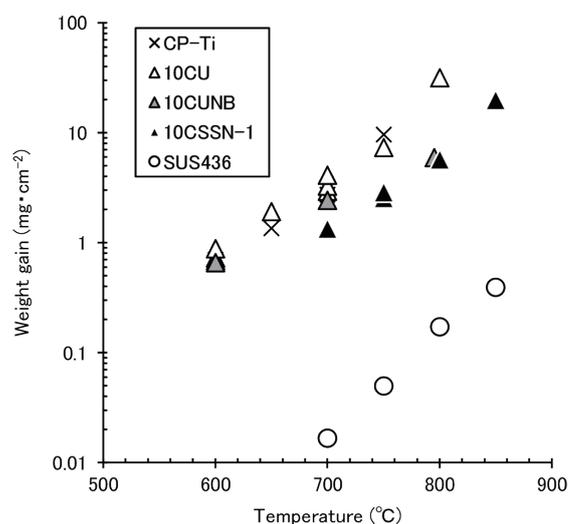

Fig. 4 Weight gain after oxidation for 200 h at various temperature in air

Table 2 Result of condensed liquid corrosion test

Material	Pitting depth (μm)		Weight loss
	Ave.	Max	(mg)
10CSSN-1	29.5	68	−0.4
SUS436	26.4	71	0.7

possesses sufficient corrosion resistance even in environments with condensed water.

3. Motor Components

Electronic devices often require non-magnetic materials to avoid interference from magnetic fields. Unlike austenitic stainless steel,[11] titanium remains non-magnetic, with a relative permeability of 1.00 even after processing (**Fig. 5**). Therefore, if its strength can be en-

hanced, titanium is expected to serve as a high-strength, non-magnetic material for components such as motor parts. This section introduces the properties of high-strength titanium alloys.
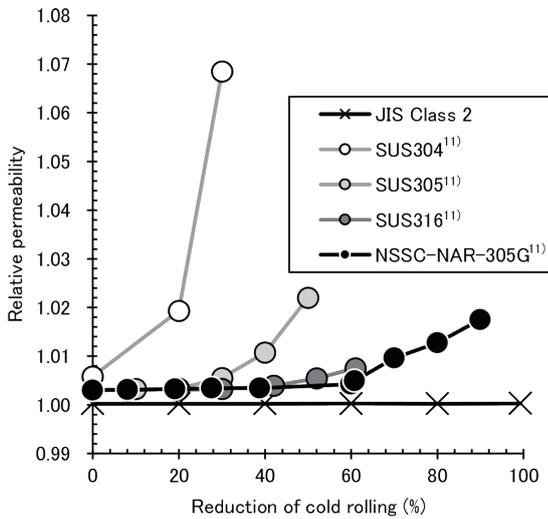
3.1 High-strength titanium alloys

Titanium alloys are generally solution-strengthened by adding large amounts of alloying elements. **Table 3** shows representative alloys and their room-temperature properties. Most $\alpha+\beta$-type titanium alloys, such as Ti-6Al-4V (Ti-64), achieve strengths of 900 MPa or higher. STIX-51AF is an alloy with strength equivalent to Ti-64 ELI[*1], offering improved cold workability and machinability. Furthermore, its fatigue strength at room temperature is equivalent to Ti-64,[12] and it has been adopted for connecting rods. STIX-523AFM is classified as a near-β type alloy within the $\alpha+\beta$ category and exhibits higher strength than Ti-64. Additionally, STIX-523AFM can be further strengthened through solution treatment and aging (STA).[13]

3.2 High strength enhancement by solution treatment and aging

Figure 6 shows the relationship between tensile strength and elongation for STIX-523AFM after solution treatment and aging. Tests were conducted on round bar stock with a parallel section of φ6 mm, a gauge length of 25 mm, and a strain rate of 30%/min. Tensile strength and elongation exhibit a trade-off relationship. Further strength enhancement is achievable by adjusting the solution

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[*1] ELI: Stands for Extra Low Interstitial, meaning the oxygen, nitrogen, hydrogen, and iron content has been further reduced.

treatment and aging conditions.

3.3 Unique shape change

STIX-523AFM not only achieves high strength through solution treatment and aging but also exhibits controllable Young's modulus, superelasticity, and shape memory properties. Furthermore, specific heat treatments induce a unique shape change where the material deforms further in the processing direction. **Figure 7** shows the shapes after bending after solution treatment at 900°C followed by holding at 200°C and 450°C. After bending at room temperature, the bending angle was 37°, and after holding at 200°C, it was 27°, exhibiting incomplete shape memory characteristics. Conversely, after holding at 450°C, the bending angle reached 57°, demonstrating a unique shape change where it deforms further in the processing direction. **Figure 8** shows the relationship between heating temperature and shape change amount.[14] Here, the shape change amount refers to the change in bending angle when the same specimen is repeatedly heated and cooled in 50°C increments from 150°C to 450°C, using the bending angle after room-temperature processing as the reference. At 900°C solution treatment (ST), incomplete shape recovery occurred up to 250°C (fully recovered at −37°), demonstrating shape memory effect. Conversely, above 300°C, shape change in the processing direction (peculiar shape change) was observed. Furthermore, at a solution treatment temperature of 930°C, the shape remained almost unchanged even after heating. These differences stem from variations in β-phase stability due to elemental distribution during solution treatment. At 900°C

Fig. 5 Relationship between relative permeability and reduction of cold rolling[11]
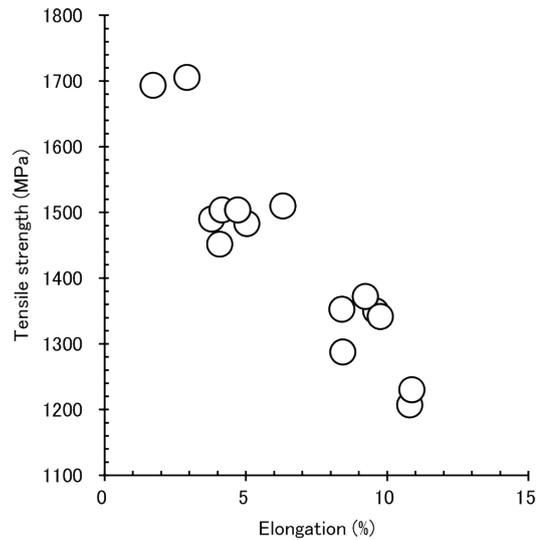
Fig. 6 Relationship between tensile strength and elongation in solution-aged STIX-523AFM bars

Table 3 Typical chemical composition and properties at room temperature in high strength titanium alloys

Materials	Chemical composition (mass%)					Tensile properties					Density (g·cm⁻³)
	Al	Fe	Mo	V	O	Heat treatment	Microstructure	0.2%PS (MPa)	TS (MPa)	El (%)	
Ti-64	6.0			4.0	≤0.20	Annealing	Equiaxed	≥828	≥895	≥10	4.43
51AF	5.0	1.0			≤0.25	Annealing	Equiaxed	≥700	≥800	≥10	4.42
523AFM	5.0	2.0	3.0		≤0.25	Annealing	Equiaxed	≥870	≥950	≥10	4.53
523AFM	5.0	2.0	3.0		≤0.25	STA	Bi-modal	≥1100	≥1200	≥10	4.53

solution treatment, the β phase is more stable. After cooling, a significant amount of β phase remains unstable but persists to room temperature, inducing a work-induced transformation (β→α" phase, body-centered orthorhombic martensite) during processing. Subsequent heating induces a reverse transformation (α"→β phase), manifesting the shape memory effect. Furthermore, heating to higher temperatures induces an isothermal transformation from β to hcp phase. At this point, variant selection occurs due to residual stresses generated during processing, likely causing the unique shape change. On the other hand, in the 930°C solution treatment, most of the β phase transforms to the α" phase after cooling. Processing then
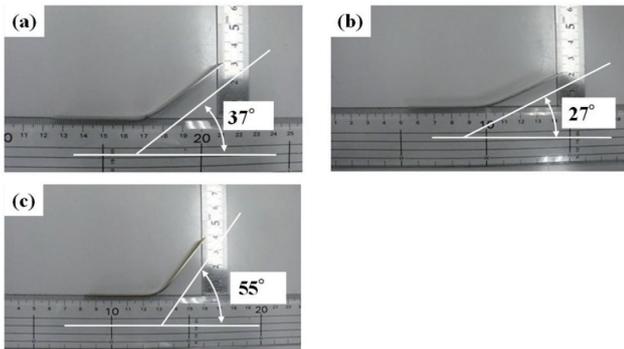

Fig. 7 Appearances of the specimen during isochronal heat treatment (a) As initially deformed by bending (before the heat treatment), (b) after heated to 200°C, and (c) subsequently heat treated to 450°C.
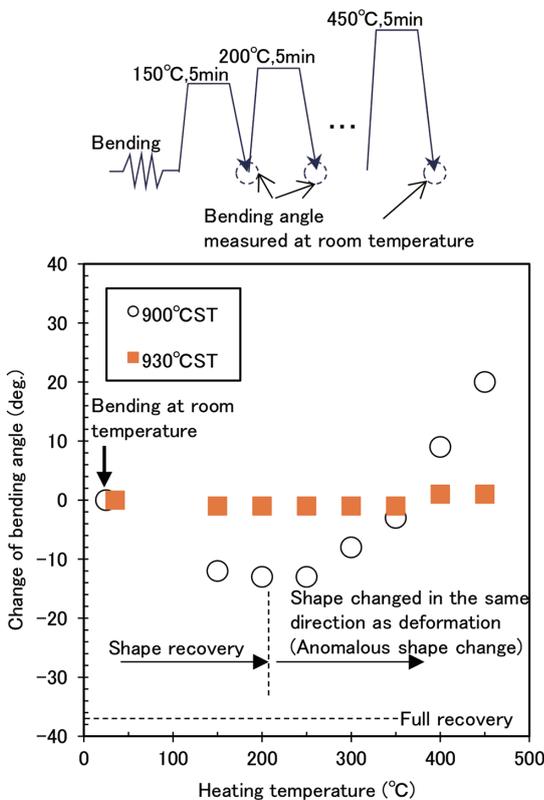

Fig. 8 Transition of bending angle during isochronal heat treatment after bending at room temperature in the specimen solution treated at 900 and 930°C followed by water quenching[14]

induces a transformation to the α' (hcp martensite) phase. This transformation to the α' phase is considered non-thermoelastic. Therefore, no reverse transformation from α' to β occurs during heating, and no shape change is expected to occur.

4. Solution Technologies for Titanium Application

Pure titanium has been successfully applied to fuel tanks (**Fig. 9**), achieving approximately 40% weight reduction compared to resin tanks. Compared to aluminum, titanium offers additional advantages exist, such as compatibility with welding equipment originally designed for steel. However, two major challenges remain: 1) Press die design—Titanium's strong in-plane anisotropy makes conventional simulation-based design insufficient. 2) Tool sticking during pressing—Titanium tends to adhere to dies, requiring effective lubrication. This section introduces Nippon Steel's approaches to these challenges, including improved press-forming simulations and lubrication technologies.

4.1 Press forming simulation

To improve the accuracy of titanium forming simulations, it is necessary to consider deformation/strength anisotropy, anisotropic hardening rule, and the Strength Differential (SD) effect. Nippon Steel has improved simulation accuracy by considering these factors.

Figure 10 shows the appearance after deep drawing test and simulation results.[15] The simulations are carried out by using the Yld2000-2d and CPB06 yield functions, which account for deformation/strength anisotropy. For CPB06, simulations were performed with and without the SD effect. As shown in Fig. 10 (a, c), an ear formed at approximately 43° relative to the rolling direction (RD) after the test. The shape of valleys exhibited anisotropy: it was flat in the RD but rounded in the rolling width direction (TD). In the simulation results without considering anisotropic hardening rule (Fig. 10 (b)), all valleys became rounded for both Yld2000-2d and CPB06 (ignoring the SD effect), failing to reproduce the flat valleys. When considering the SD effect with CPB06, ears formed at positions where the valley was flat in the experiment, failing to reproduce the experimental results. On the other hands, in those with considering the anisotropic hardening rule, the results closer to the experiments for both yield functions. Particularly, in the result considering the SD effect with CPB06, the appearance became closer to the experiment, and the cup height (Fig. 10 (c)) also matched the experiment almost exactly.

As described above, it is evident that considering not only defor-
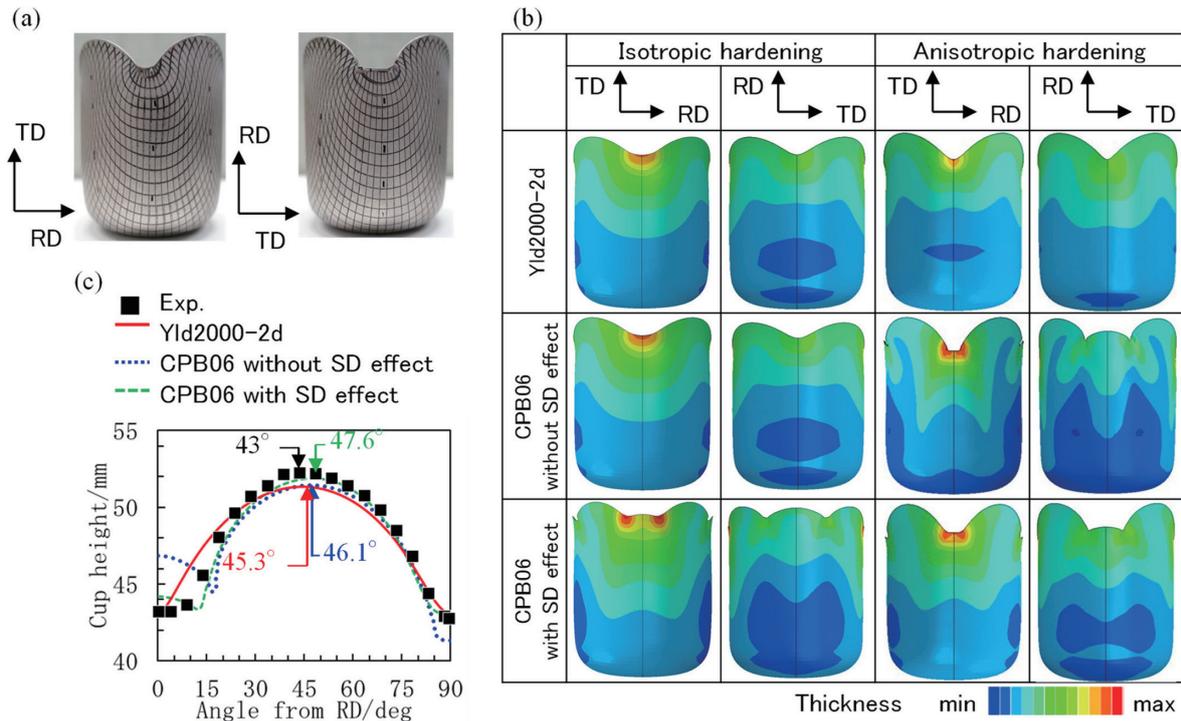

Fig. 9 Titanium fuel tank

Fig. 10 Experimental and simulation results in cylindrical deep drawing[15]
(a) Appearance after cylindrical deep drawing test, (b) deformed shapes and thickness distribution, and (c) cup height profiles of the simulation using Yld2000-2d, CPB06 without SD effect, and CPB06 with SD effect yield criteria with isotropic and anisotropic hardening rules.

mation/strength anisotropy but also anisotropic hardening rule and the SD effect contributes to improving simulation accuracy. Furthermore, acquiring material data for simulation is also crucial. Nippon Steel will continue to strive for further accuracy improvements and support the application of titanium processing.

4.2 Lubricity

To prevent sticking, solid lubricants such as sheets or dry film types may be used to avoid contact between the die and titanium. However, considering productivity, the use of conventional liquid lubricants is preferable. For thin titanium sheets, two annealing processes are performed: annealing+pickling or vacuum atmosphere annealing. Vacuum atmosphere annealing forms a thin oxide film on the surface, and partially modifying the die material reduces sticking to the die, enabling the use of liquid lubricants.[16]

Tribology research is essential for improving lubricity. Nippon Steel conducts detailed investigations of sliding behavior and develops technologies considering factors like the crystal orientation of grains directly beneath the sliding surface. **Figure 11** shows the relationship between the Taylor factor directly beneath the sliding surface and the friction coefficient.[17] It reveals that the influence of crystal orientation directly beneath the sliding surface varies with vertical load. **Figure 12** shows a schematic diagram of the presumed mechanism for the effect of grain orientation directly beneath the sliding surface on the friction coefficient.[17] When the vertical load is small, grain deformation does not occur, so there is no effect. Conversely, as the vertical load increases, deformation occurs in the grains directly beneath the sliding surface, with grains having lower Taylor factors deforming more significantly. This leads to an increase in the true contact area and the effects of digging, causing the friction coefficient to rise. Furthermore, as the vertical load increases
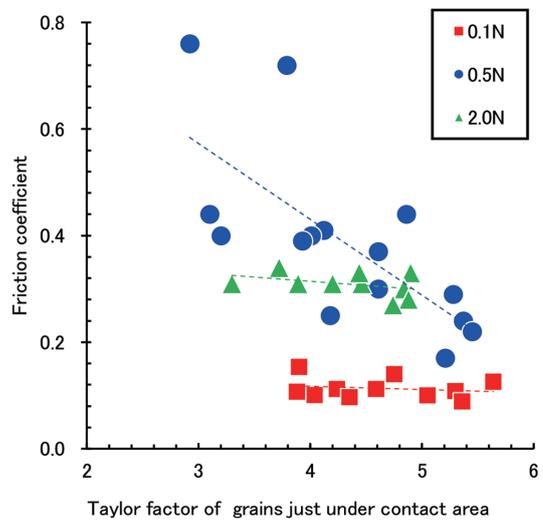

Fig. 11 Relationship between friction coefficient and Taylor factor of crystal grains immediately below the contact surface in the edge sliding test of IP block at the vertical load of 0.1 N, 0.5 N, and 2.0 N[17, 18]

even more, deformation occurs simultaneously in many grains, averaging out the deformation and making fluctuations less likely. Thus, since material microstructure also affects lubricity, we will pursue optimal material development, including microstructure control, to reduce lubricant usage and contribute to lowering environmental impact.
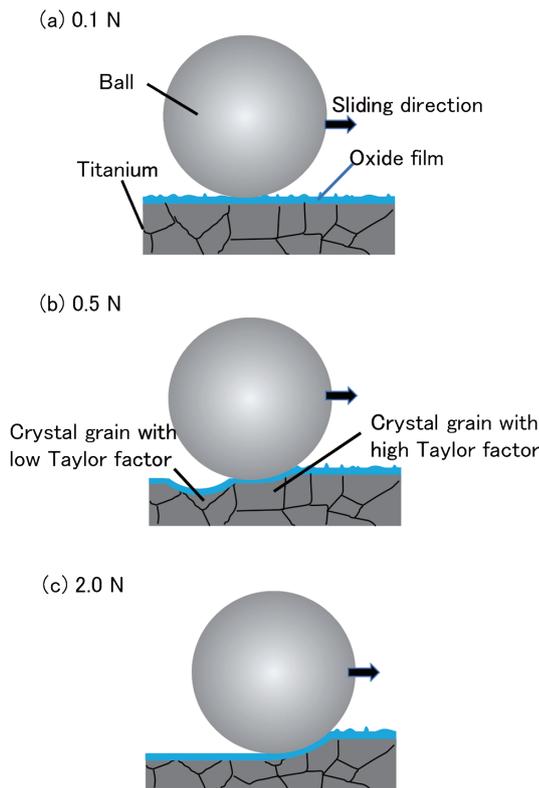
(a) 0.1 N
Ball
Sliding direction
Titanium
Oxide film

(b) 0.5 N
Crystal grain with low Taylor factor
Crystal grain with high Taylor factor

(c) 2.0 N

Fig. 12　Schematic diagrams of sliding form of edge sliding test at the vertical load of (a) 0.1 N, (b) 0.5 N, and (c) 2.0 N[17, 18]

5. Summary

This paper introduced the characteristics of titanium and several solution technologies developed Nippon Steel for automotive applications. Moving forward, as a materials manufacturer, we will continue to share information on titanium and contribute to advancements in the automotive industry through collaboration with component manufacturers and automakers.

References

1) Takahashi, M.: Engineering Materials. 65 (12), 21 (2017)
2) Chiba, K.: Engineering Materials. 65 (12), 16 (2017)
3) Fujii, H., Takahashi, K.: Shinnittetsu Giho. (375), 99 (2001)
4) Nakamura, S.: Denki-Seiko. 60 (3), 272 (1989)
5) Isaka, M., Takebe, H., Kawakami, S., Takahashi, K.: Nippon Seitetsu Giho. (418), 33 (2021)
6) Takebe, H., Takahashi, K.: Nippon Seitetsu Giho. (412), 190 (2019)
7) Otsuka, H.: Titanium Japan. 60 (2), 26 (2012)
8) Yashiki, T.: Titanium Japan. 59 (1), 7 (2011)
9) Hara, M., Inoue, M., Nakagawa, T.: Journal of the Japan Institute of Metals and Materials. 62 (8), 691 (1998)
10) Mori, K., Takahashi, K., Fujii, H., Otsuka, H.: Proc. 13th World Conf. on Titanium, San Diego, 2015, (The Minerals, Metals & Materials Society, 2016), p. 1883–1838
11) NSSC-NAR-305G, Nippon Steel Corporation, https://www.nipponsteel.com/product/stainless/nssc/product/grade/nssmc_series/product/nssmc-nar-305g.html (Accessed 2025-04-28)
12) Doi, K., Kubota, T., Murakami, T., Kojima, Y., Miura, T.: Titanium Japan. 64 (1), 40 (2016)
13) Mori, K., Takebe, H., Hashimoto, S.: Nippon Seitetsu Giho. (418), 97 (2021)
14) Kunieda, T., Fujii, H., Takahashi, K., Wada, K., Takemoto, Y.: CAMP-ISIJ. 25, 1285 (2012)
15) Nishiyama, S., Tsukamoto, G., Miyoshi, R., Okamura, K.: Transactions of the Japan Society of Mechanical Engineers. 9 (928), (2023)
16) Kawakami, S.: Bull. Iron Steel Inst. Jpn. 23 (11), 6 (2018)
17) Miyoshi, R., Tsukamoto, G.: Tetsu-to-Hagané. 109 (9), 761 (2023)
18) Miyoshi, R., Tsukamoto, G.: ISIJ International. 64 (12), 1804 (2024)
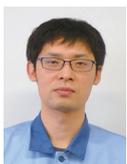
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