Polyacetal copolymer

Iupital™

Design Guide

GLOBAL POLYACETAL

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Iupital has excellent strength, durability, abrasion resistance, chemical resistance, etc., and can be used for various kinds of gears.

Gear failure results from a combination of tooth fatigue and surface wear, necessitating strength design considerations for both mechanisms.

1.1 Gear design

1.1.1 Dental strength

In general, Lewis equation (1) is used for the bending stress applied to the tooth root.

$$W = S \cdot b \cdot m \cdot (y') \qquad \cdots (1)$$

S: Flexural stresses (kg/m m²) on the root

m: Module (mm)......Diametric pitch: $P_d = \frac{25.4}{m}$

b: Tooth width (mm)

(y'): Dental profile factor (reference Table 1.1.1-1)

W: Pitch-circumferential tangential load (kg)

Table 1.1.1-1 Gear profile factor of spur gear

Angle of pressure 20° Standard gear						Angle of pressure 14.5° standard gear					
Number of gears z	y(y')		z	y(y')		Number of gears z	y(y')		z	y(y')	
12	0.277	0.415	60	0.433	0.713	12	0.237	0.355	60	0.365	0.603
13	0.292	0.443	75	0.443	0.735	13	0.249	0.377	75	0.369	0.613
14	0.308	0.468	100	0.454	0.757	14	0.261	0.399	100	0.374	0.622
15	0.319	0.490	150	0.464	0.779	15	0.270	0.415	150	0.378	0.635
			300	0.474	0.801				300	0.385	0.650
16	0.325	0.503	Rack	0.484	0.823	16	0.279	0.430	Rack	0.390	0.660
17	0.330	0.512				17	0.288	0.446			
18	0.335	0.522				18	0.293	0.459			
19	0.340	0.534				19	0.299	0.471			
20	0.346	0.543				20	0.305	0.481			
21	0.352	0.553				21	0.311	0.490			
22	0.354	0.559				22	0.313	0.496			
24	0.359	0.572				24	0.318	0.509			
26	0.367	0.587				26	0.327	0.522			
28	0.372	0.597				28	0.332	0.534			
30	0.377	0.606				30	0.334	0.540			
34	0.388	0.628				34	0.342	0.553			
38	0.400	0.650				38	0.347	0.565			
43	0.411	0.672				43	0.352	0.575			
50	0.422	0.694				50	0.357	0.587			

1.1.2 Tooth surface strength

The gear tooth surface is subject to damage phenomena such as pitting or wear, and the Hertzian equation (2) is generally used to calculate gear stress.

$$W = \sigma_{\alpha}{}^{2} - b d_1 \quad \cdots\cdots\cdots\cdots\cdots\cdots (2)$$

$$\frac{\sin 2\alpha}{2.8}\left(\frac{2Z_2}{Z_1+Z_2}\right)\left(\frac{1}{E_1}+\frac{1}{E_2}\right)$$

W: Pitch-circumferential tangential load (kg)
b: Tooth width (mm)
$d1$: Gear pitch-circle diameter (mm)
α: Meshing pressure angle
$Z1$: Number of teeth in the gear
$Z2$: Number of teeth in the pinion
$E1$: Modulus of longitudinal elasticity of gear (kg/mm^2)
$E2$: Longitudinal modulus of the pinion (kg/mm^2)
$\sigma\alpha$: Allowable compressive stress

1.2 Tooth fatigue strength and surface strength

The bending stress and the surface pressure which lead to fatigue fracture and wear damage of gears vary depending on the size of teeth and the operating conditions.Longevity of teeth is affected by seven factors, requiring a comprehensive assessment.

1) High and low actual operating temperatures
2) Presence or absence of lubrication
3) Material used for gears for power transmission
4) Operation status (continuous operation, intermittent operation)
5) Power transmission speed
6) Wear of contact surface
7) Meshing ratio

Figs. 1.2-1 and 1.2-2 show the fatigue resistance and surface pressure strength of gears.

Gear strength S-N curve

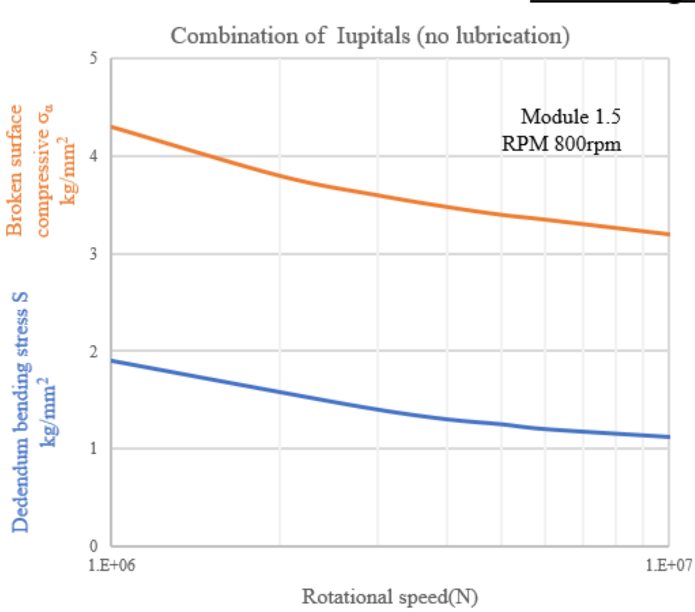


Fig. 1.2-1 Relationship between gear strength and cycle

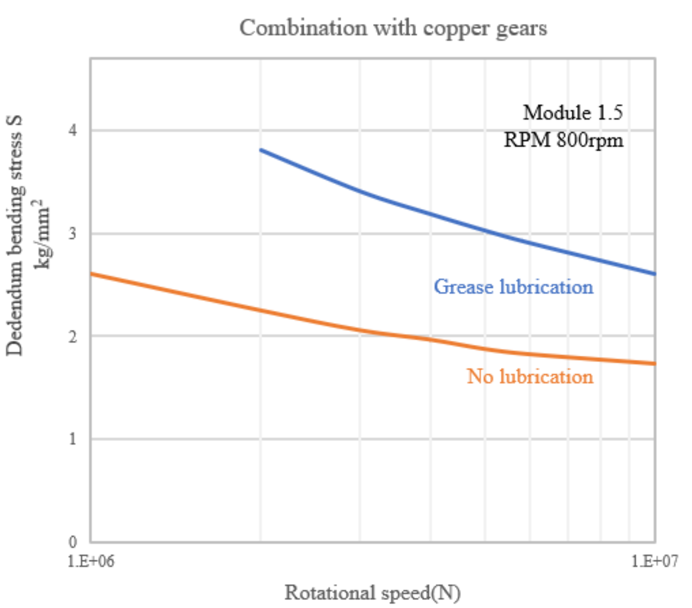


Fig. 1.2-2 Relationship between gear strength and cycle

2.1 Metal insert

There are two insertion methods: insertion during molding and insertion after molding. After molding insert method is described below.

Figures 2.1-2 to 2.1-4 show the results of inserting brass-made insert fittings (7mmφ x 13mmL). These results indicate the following.

1) An upward convex relationship exists between wall thickness ratio, pulling force, rotational torque, and a peak occurs near a ratio of 2.0. Below this ratio, reduced material mechanical retention weakens the values. Above it, the sink effect in the thickness direction causes a decrease.
2) The value of the pulling force and the rotational torque by the heat treatment is increased overall. This is considered to be a heat shrinkage effect.
3) By providing a knurled groove, the holding force is greatly improved.
4) As shown in Figure 2.1-5, the stress generated around the insert is calculated from the pull-out force. This was calculated by the following formula:

$$\sigma_{\max} = FW/\pi D_S L\mu$$

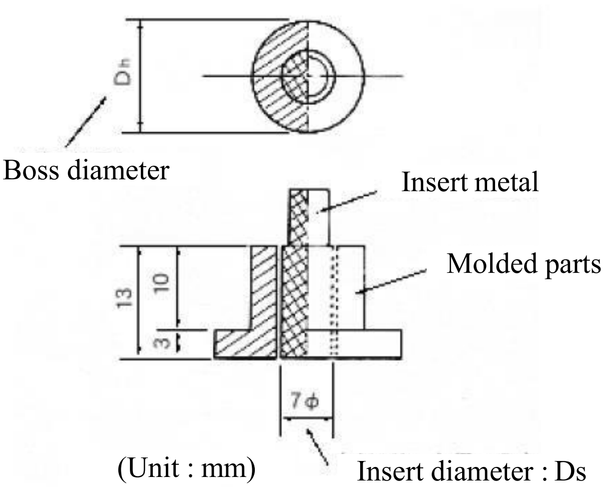
$\sigma_{\max}$ =Max Tensile Stress (kg/cm^2)
W: K^2+1/K^2-1
F: Pullout force (kg),
μ: Coefficient of Friction (0.15)
$K = Dh/Ds$ (Boss outer diameter/Insert fitting diameter)
L: Insert-metal fitting length (cm)

To prevent cracking around molded-in inserts in Iupital, careful attention to the following three key factors is essential.

1) Stress concentration by sharp edges on metal inserts
2) Weld line(s)
3) Increased stress from long-term heat exposure.

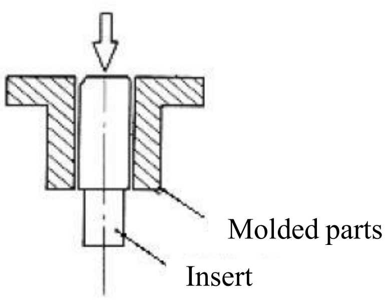
For example, in the test shown in FIG. 2.1-2 (*with a knurled metal fitting*), was heat aged for 3,000〜4,000hr at 75 ° C., cracks are generated from the sharp edge weld portion of the knurled insert.

(1) Shape of test specimen



(2) Measurement method

i) Pull-out force (Axis holding force)



ii) Rotation torque
(Circumferential holding force)

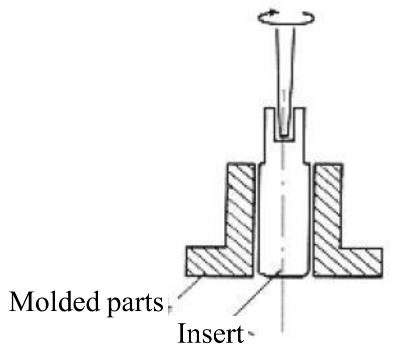


Fig. 2.1-1 Insert Molded Product Shape and Insert Holding Force Measurement Method

Pull out force for metal insert after molding(*Insert fitting: 7mmφ x 13mmL brass*)

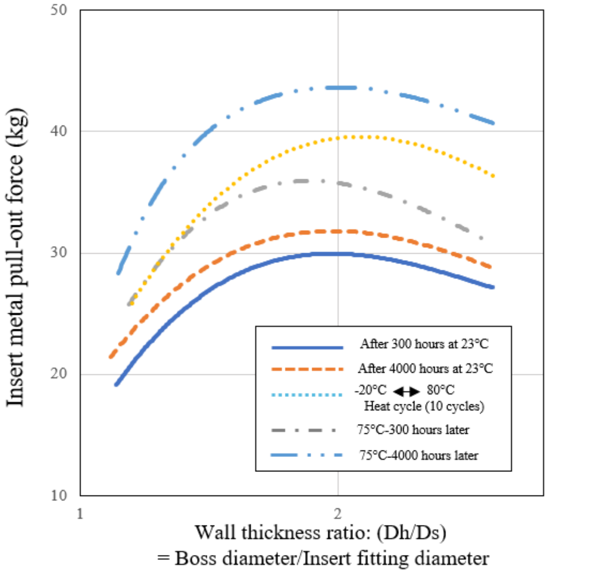


Fig. 2.1-2 Insert metal fitting pull-out force without knurling

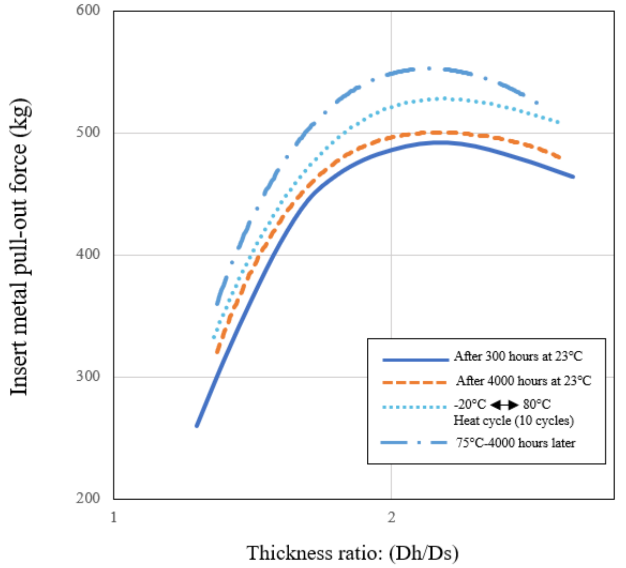


Figure 2.1-3 Insert Bracket Pull-out Force with Knurled

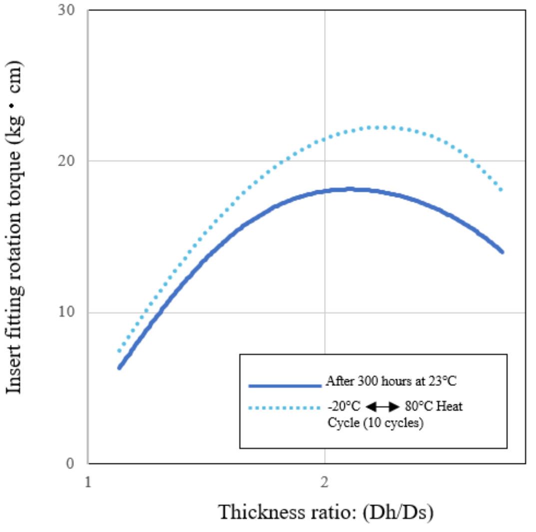


Fig. 2.1-4 Insert metal fitting rotation torque without knurl

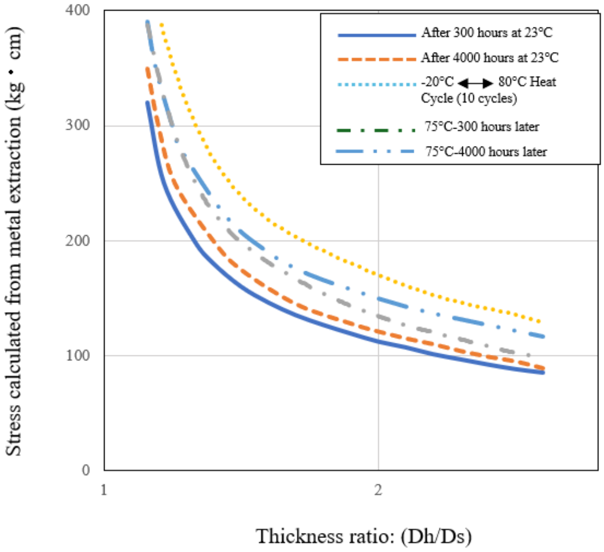


Fig. 2.1-5 Stress at each wall thickness ratio
(calculated from metal fitting pull-out force without knurling)

2.2 Fastening with self-tapping screws

The self-tapping screw characteristics of Iupital were investigated using a Iupital test piece as shown in Fig. 2.2-1 and changing the diameter of the lower hole (catch ratio), boss outer diameter, screw depth, etc., for a self-tapping screw with a nominal diameter of 3mmφ. Here, the catch ratio is not exactly defined in the case of self-tapping screw, but it was calculated as follows.

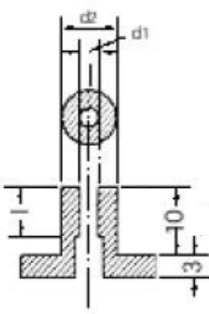
$$Thread\ engagement(\%) = \frac{D(External\ Thread\ Outer\ Diameter) - d_1(Hole\ \ diameter)}{D(External\ Thread\ Outer\ Diameter) - D_1(External\ Thread\ trough\ diameter)}$$

The results are as shown in Figures 2.2-2 to 2.2-5. These results indicate the following.

1) The larger the seizure rate and the screw depth, the larger the pull-out force breaking torque and screw-in torque of the screw, etc.
2) Regarding the boss wall thickness, when the contact ratio is large, or the wall thickness is thick, pulling force, breaking torque, etc. are increased.
3) Fracture torque is improved with heat treatment or heat cycle treatment, the return torque tends to decrease.

When Iupital molded products are fastened with self-tapping screws, the larger the catch ratio, the higher the breaking torque and pulling force, but the larger the screwing torque and the worse the workability. To increase the breaking torque and pulling force without significantly reducing the workability, it is better to increase the screw-in depth. Thickness of the boss part should be 1/2 or more of the diameter of the screw. However, if it is too thick, it will generate a sink mark, and can reduce the screw thread engagement.

(1) Shape of test specimen

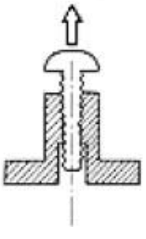


(Unit: mm)

(2) Measurement method

d1 : hole size before threading
d2 : Boss outer diameter
l : Screw depth

Measurement of pull-out force (by autograph)



Measurement of torque (by torque meter)

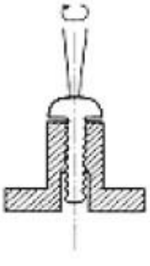
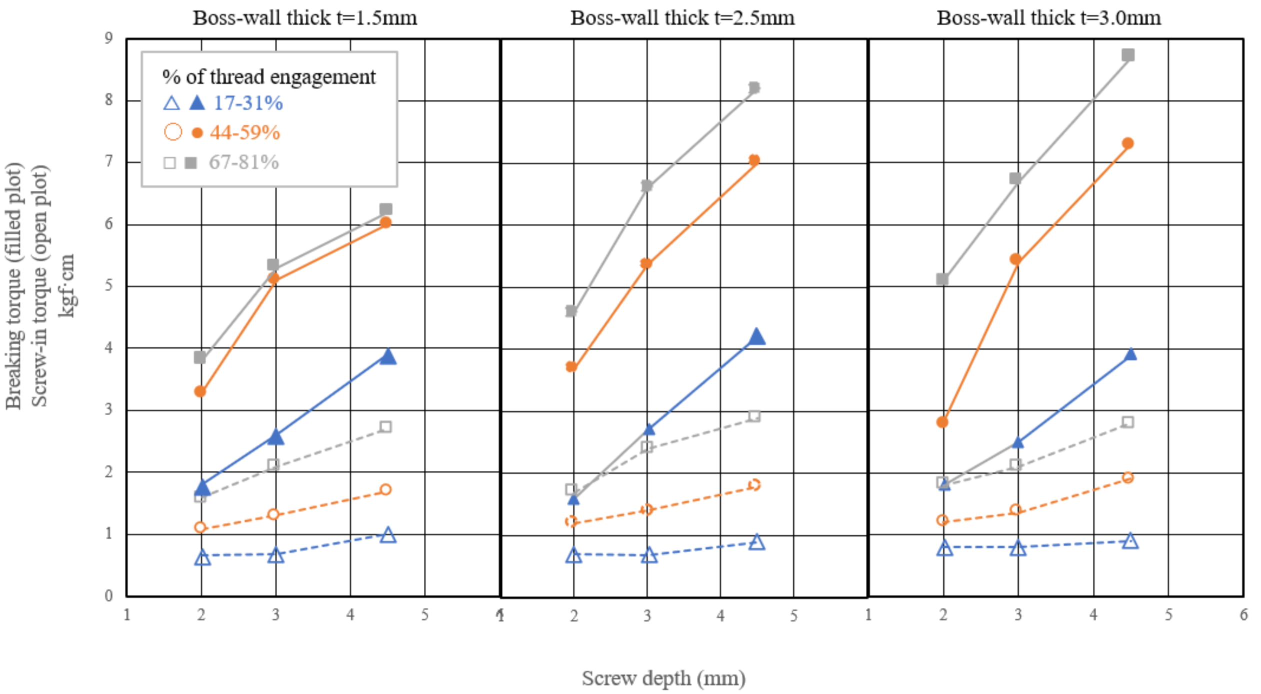


Fig. 2.2-1 Self-tapping screw tightening

(1) Screw-in torque and breakdown torque

※Screw: cross recessed tapping screw, type 2 with groove, nominal diameter: 3mm, depending on JIS B1122



(2) Pull-out force of the screw

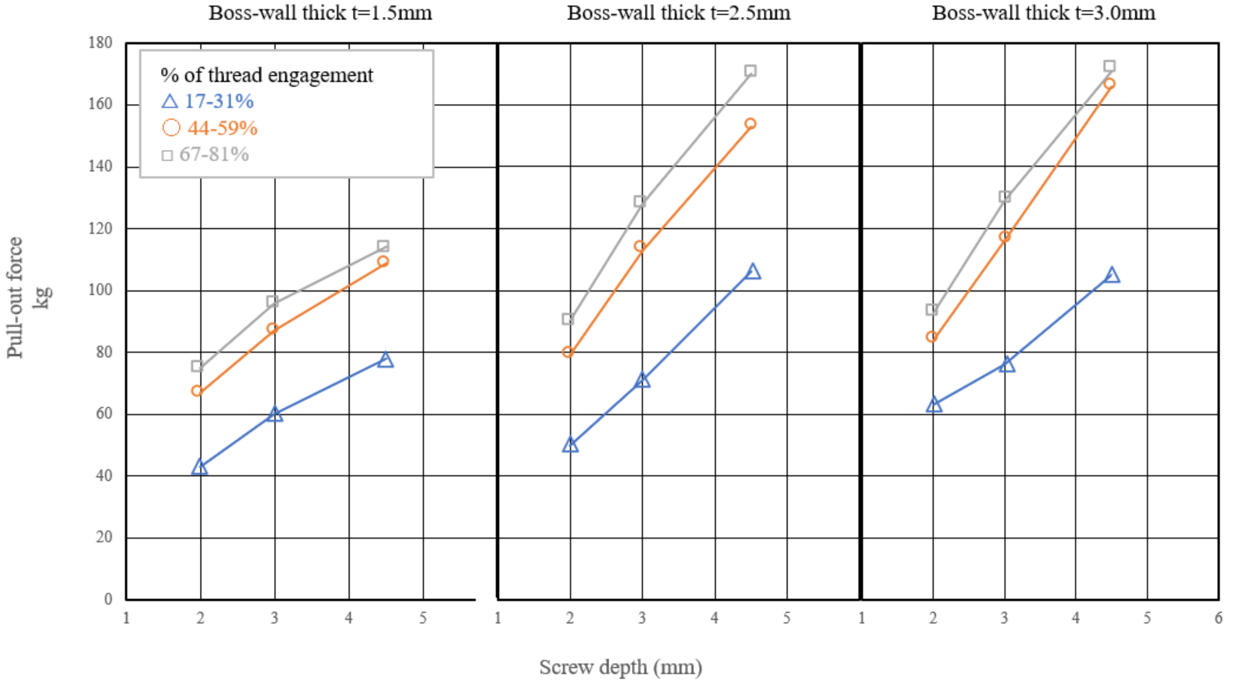
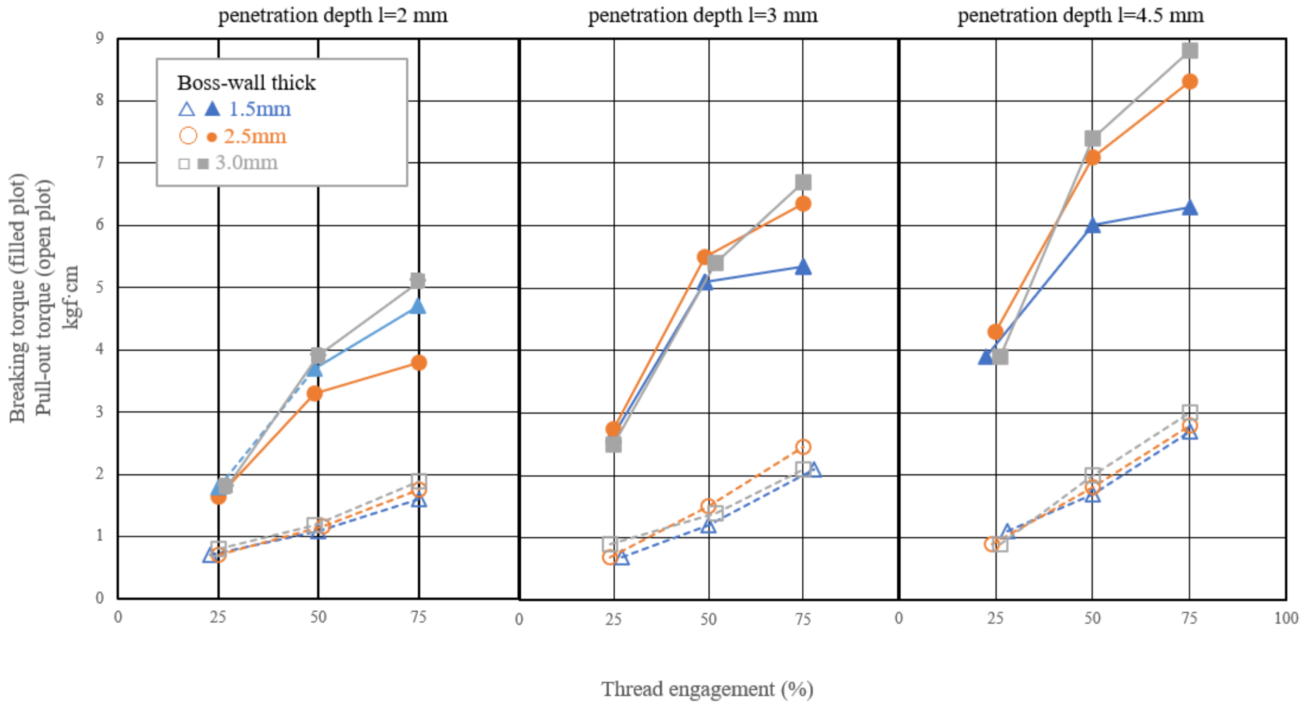


Fig. 2.2-2 Fastening screw depth with self-tapping screw

(1) Screw-in torque and breakdown torque

※Screw: cross recessed tapping screw, type 2 with groove, nominal diameter: 3mm, depending on JIS B1122



(2) Pull-out force of the screw

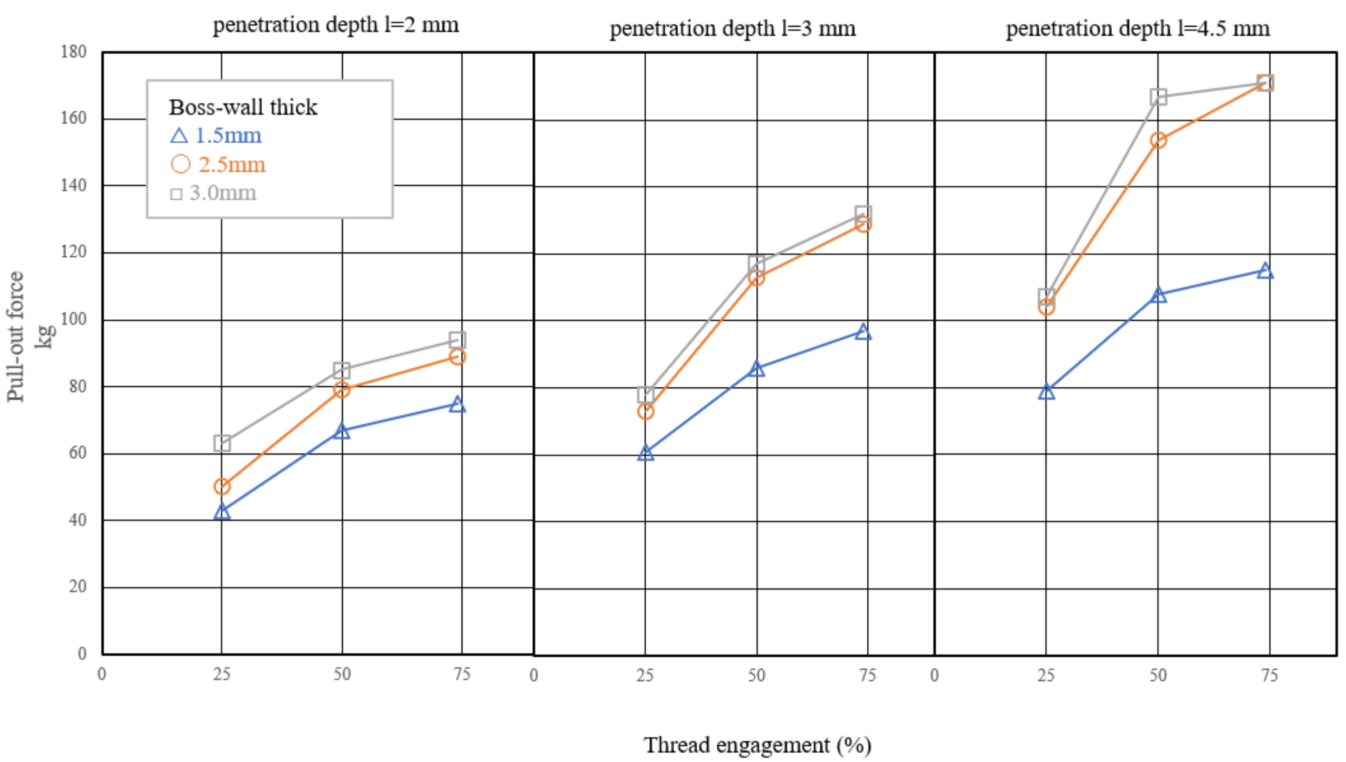


Fig. 2.2-3 Effect of Bottom Hole Diameter by Self-Tapped Screws

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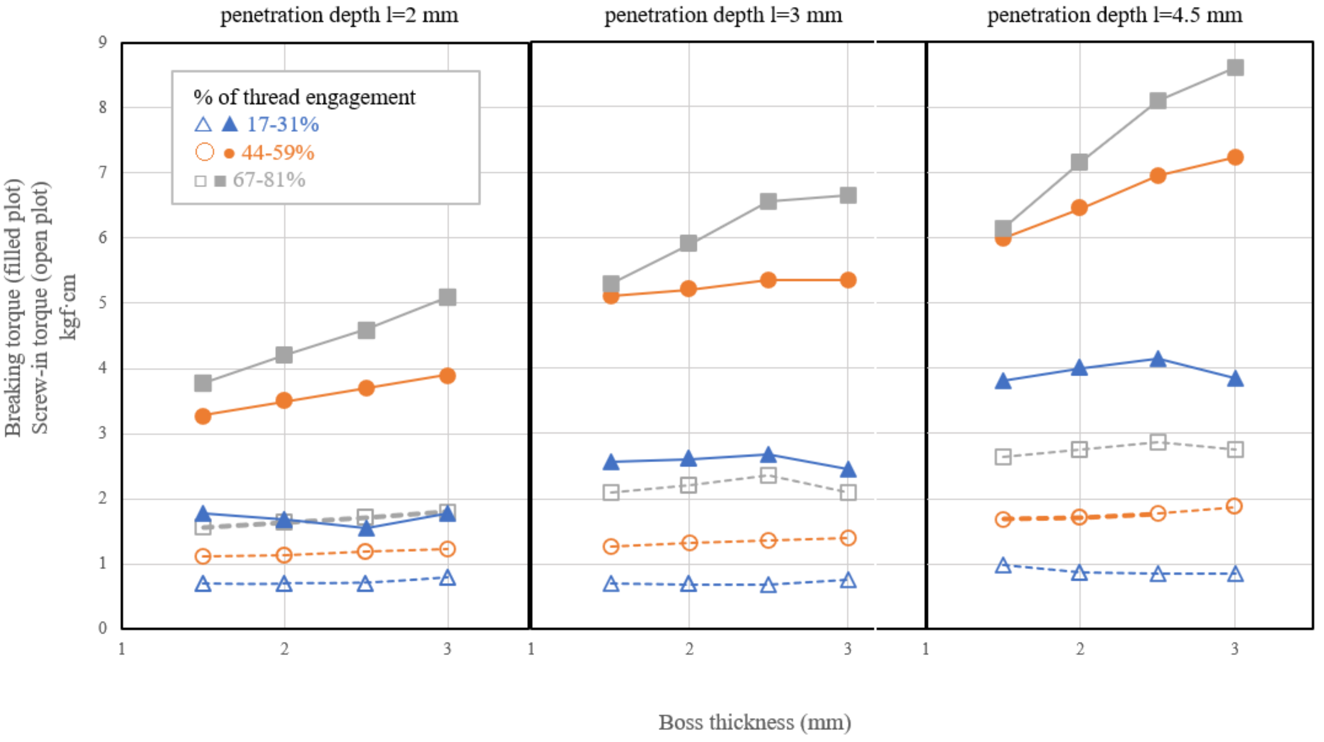
(1) Screw-in torque and breakdown torque

※Screw: cross recessed tapping screw, type 2 with groove, nominal diameter: 3mm, depending on JIS B1122



(2) Pull-out force of the screw

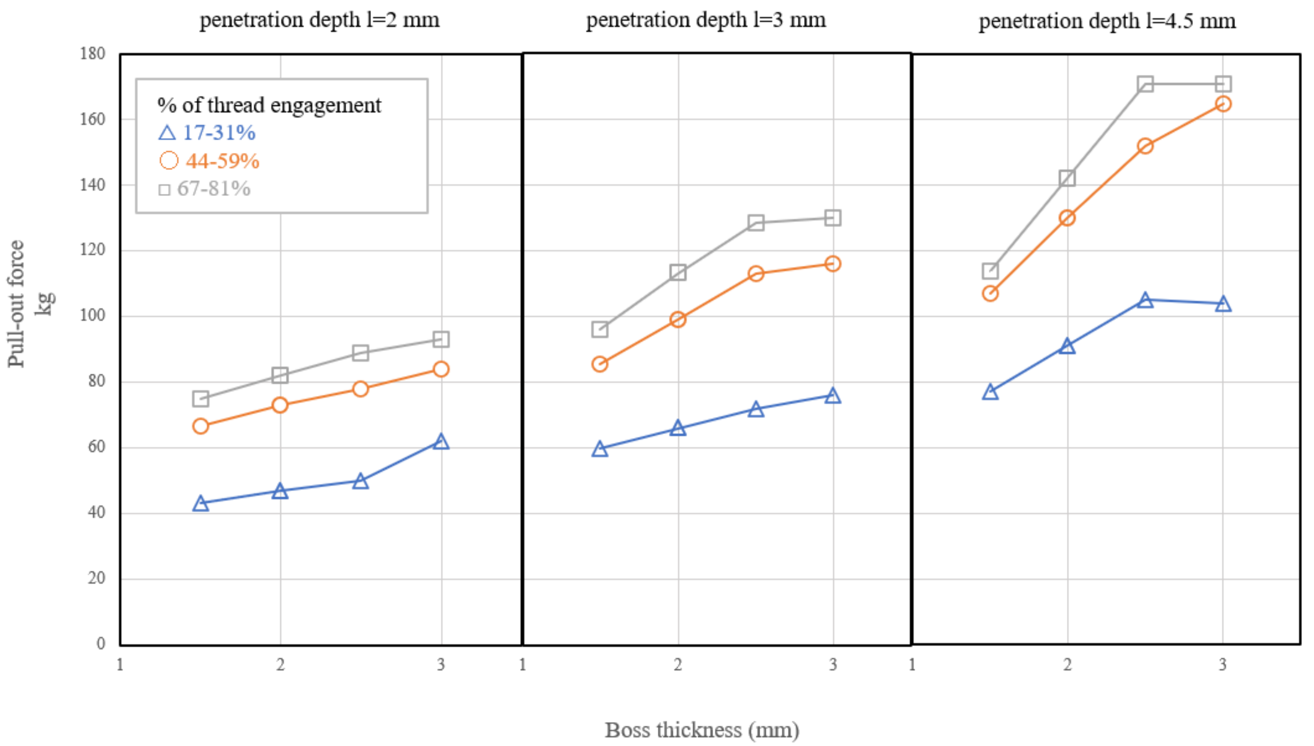


Fig. 2.2-4 Effect of Boss Wall Thickness Using Self-Tapped Screws

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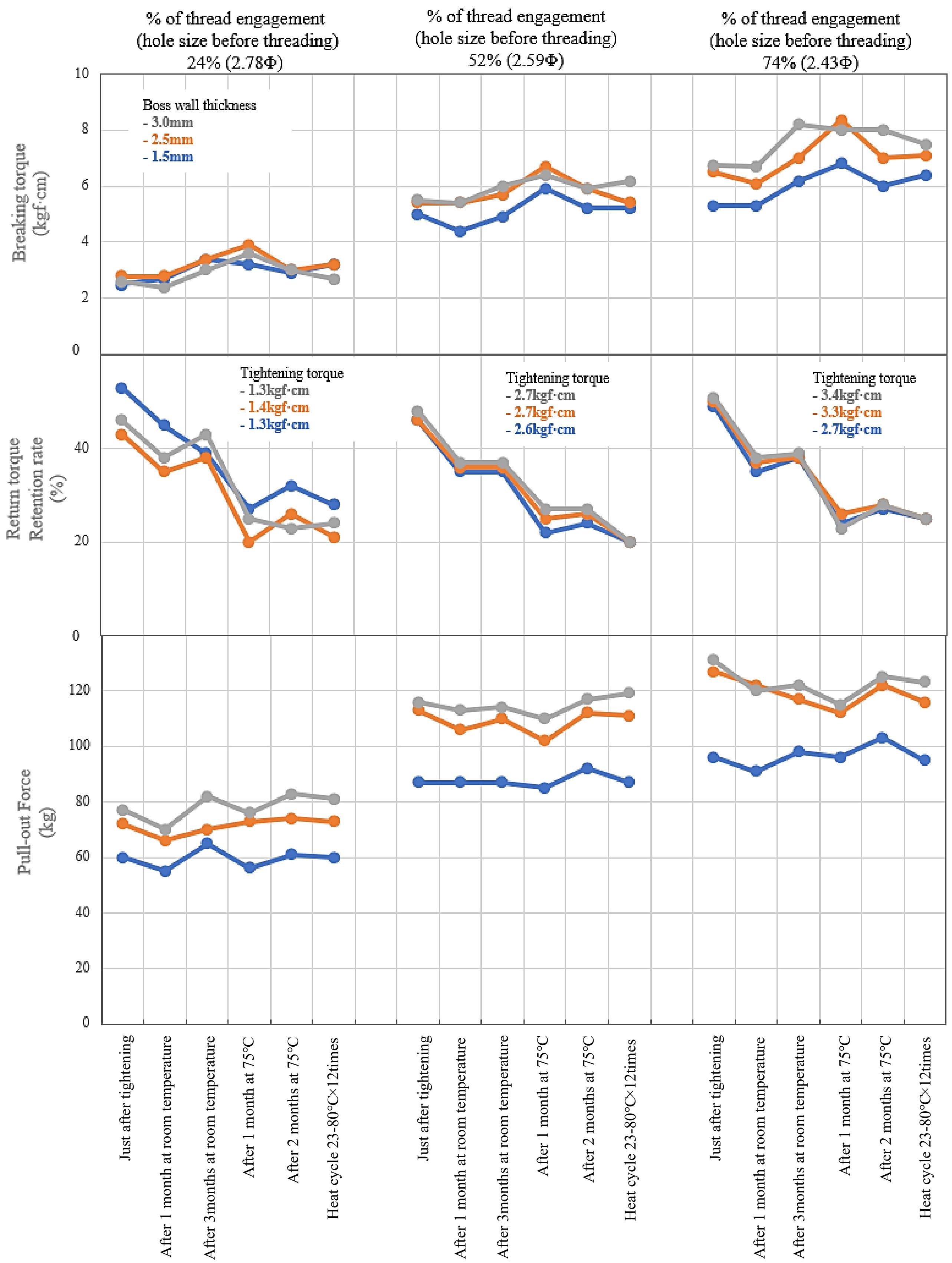

Figure 2.2-5 Long-term Fastening Test for Self-Tapped Screws

2.3 Tightening with metal machine screws

As shown in Fig. 2.3-1, changes in the return torque and the tightening force after tightening Iupital molded product with a metal machine screw were examined.
The tightening force Q generated on the screw was calculated from the torque T by the following equation.

$$Q = 2T/\{d2\ \tan(\rho \pm \beta) + \mu n\ dn\}$$

Here, the relation between the tightening torque Tf and the tightening force Qf for the case of sign + and the return torque Tr and the tightening force Qr for the case of sign-is shown.

d2: Screw effectiveness

μ: Coefficient of friction of engaged thread (calculated as 0.20)

θ: Thread angle

tan ρ=μ/cos(θ/2)

p:Pitch

β:lead angle of the screw (tan β=P/πd2)

μn: Coefficient of friction at bearing surface (calculated as 0.15)

dn: Mean diameter at bearing surface *refer Fig. 2.3-2: (B+d')/2

The results, depicted in Figures 2.3-3 through 2.3-6, indicate that prolonged exposure leads to a decrease in both return torque and tightening force due to stress relaxation. This reduction is especially noticeable under high loads. Consequently, applications susceptible to loosening may necessitate the use of spring washers or other anti-loosening mechanisms. Conversely, heat treatment and heat cycling of the Iupital fastening did not result in any observed cracking.

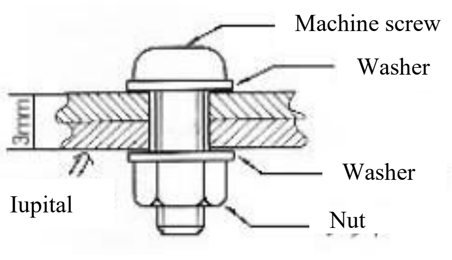

Fig. 2.3-1 Test Method for Fastening with Metal Screws

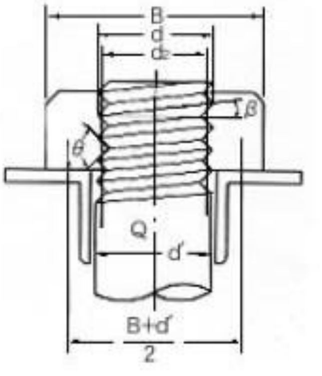

Fig. 2.3-2 Shape of tightening part

To prevent deformation or insufficient clamping force in the Iupital fastening, the tightening torque should be within ±20% of the values in the table. A higher torque within this range is preferable when looseness is a risk, while a lower torque can improve workability and safety.

Table 2.3-1 Tightening torque standard of machine screw

Nominal size	M3	M4	M5	M6
Tightening torque standard kgf・cm	7.5	20	35	50

Tightened with a torque of 5 kgf ・ cm, the return torque after treatment is indicated by □, and the tightening force (Qr) is indicated by ●.
Tightened with a torque of 7.5 kgf・cm, the return torque after treatment is indicated by □, and the tightening force (Qr) is indicated by ▲.
Tightened with a torque of 10 kgf・cm, the return torque after treatment is indicated by □, and the tightening force (Qr) is indicated by ■.

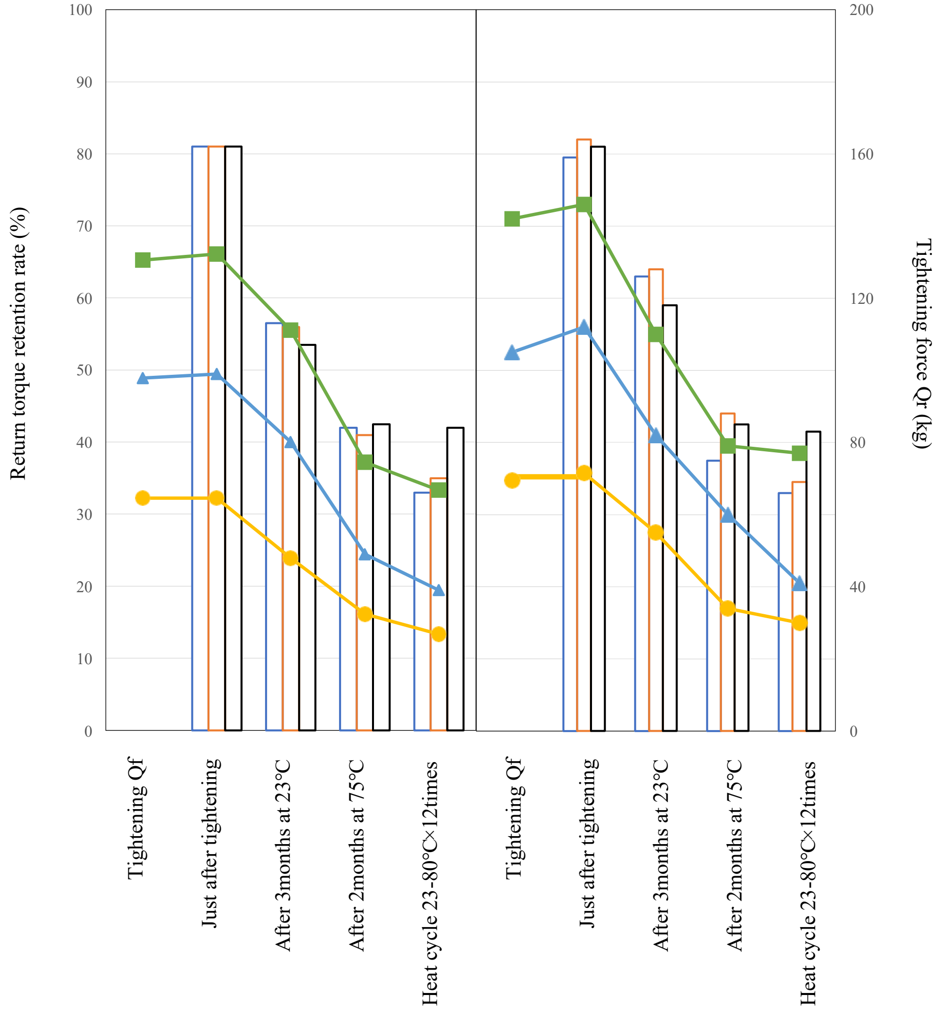

Fig. 2.3-3 M3 Return Torque Holding Rate and Tightening Force after Long-term Tightening of Small Screw

Tightened with a torque of 10 kgf・cm, the return torque after treatment is indicated by □, and the tightening force (Qr) is indicated by ●.
Tightened with a torque of 20 kgf・cm, the return torque after treatment is indicated by □, and the tightening force (Qr) is indicated by ▲.
Tightened with a torque of 30 kgf・cm, the return torque after treatment is indicated by □, and the tightening force (Qr) is indicated by ■.

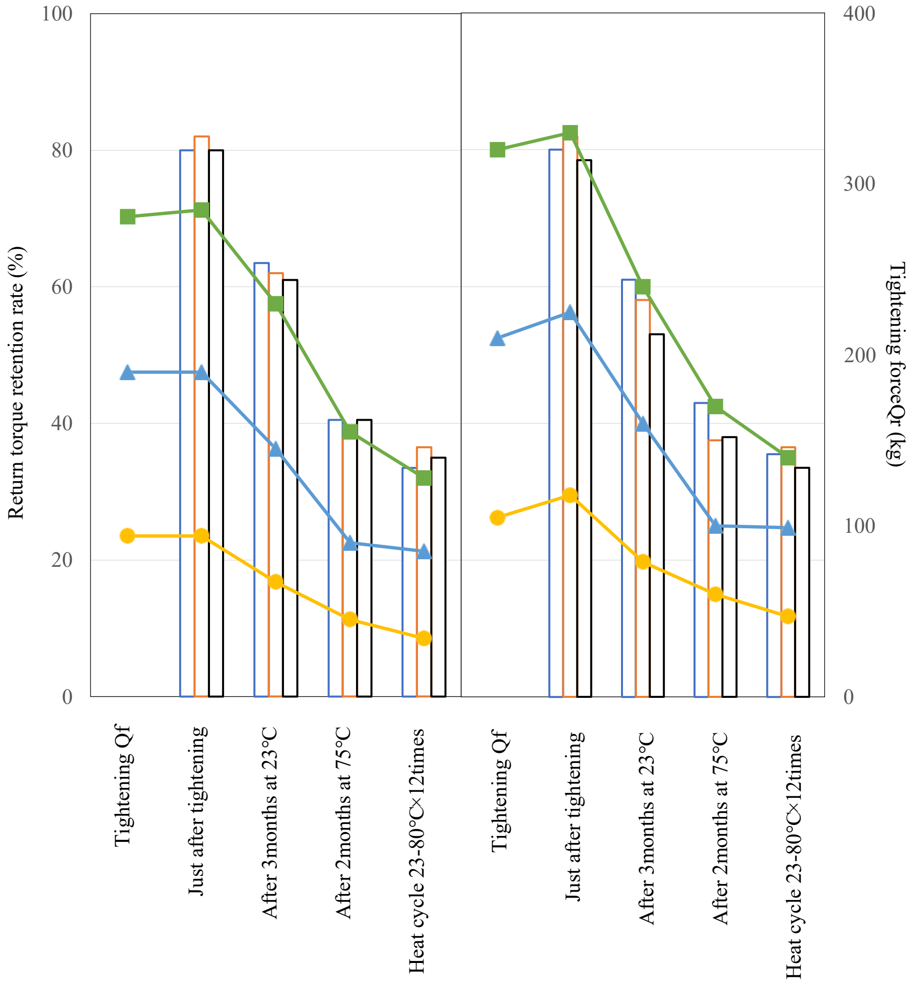

Fig. 2.3-4 M4 Return Torque Holding Rate and Tightening Force
after Long-term Tightening of Small Screw

Tightened with a torque of 20 kgf・cm, the return torque after treatment is indicated by □, and the tightening force (Qr) is indicated by ●.
Tightened with a torque of 35 kgf・cm, the return torque after treatment is indicated by □, and the tightening force (Qr) is indicated by ▲.
Tightened with a torque of 50 kgf・cm, the return torque after treatment is indicated by □, and the tightening force (Qr) is indicated by ■.

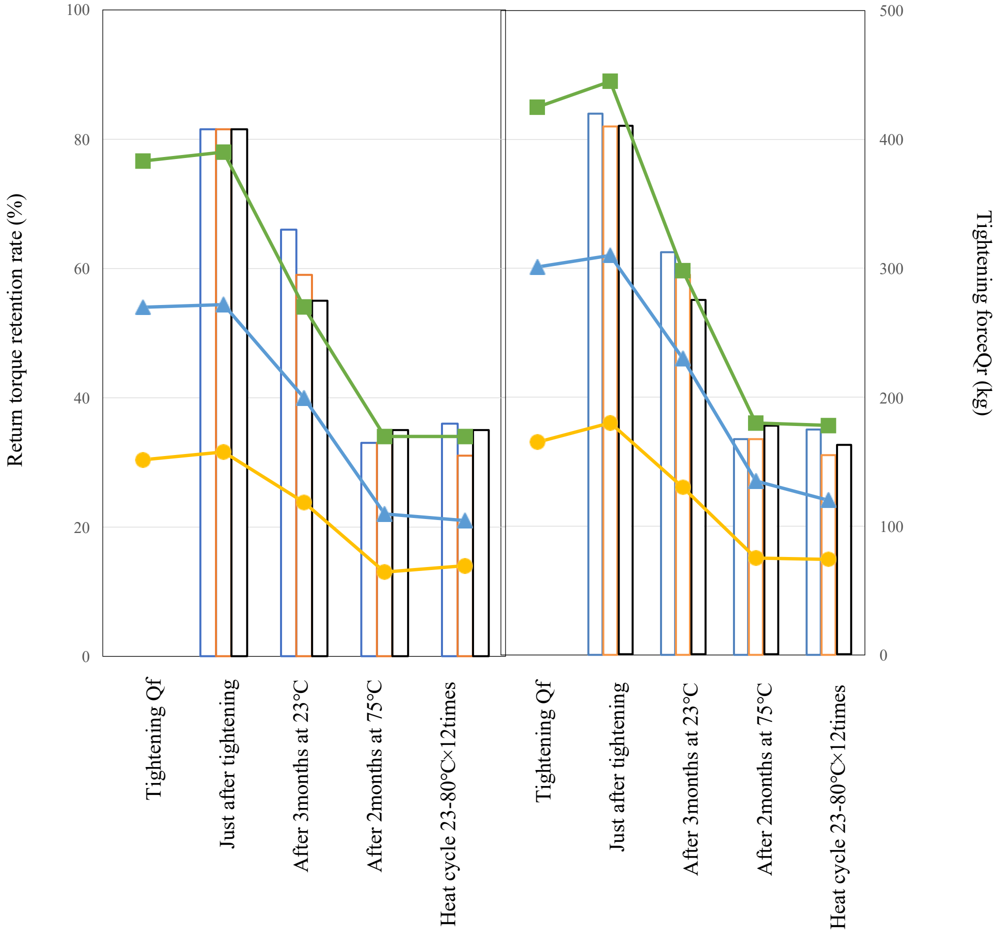

Fig. 2.3-5 M5 Return Torque Holding Rate and Tightening Force after Long-term Tightening of Small Screw

Tightened with a torque of 20 kgf・cm, the return torque after treatment is indicated by □, and the tightening force (Qr) is indicated by ●.
Tightened with a torque of 50 kgf・cm, the return torque after treatment is indicated by □, and the tightening force (Qr) is indicated by ▲.
Tightened with a torque of 80 kgf・cm, the return torque after treatment is indicated by □, and the tightening force (Qr) is indicated by ■.

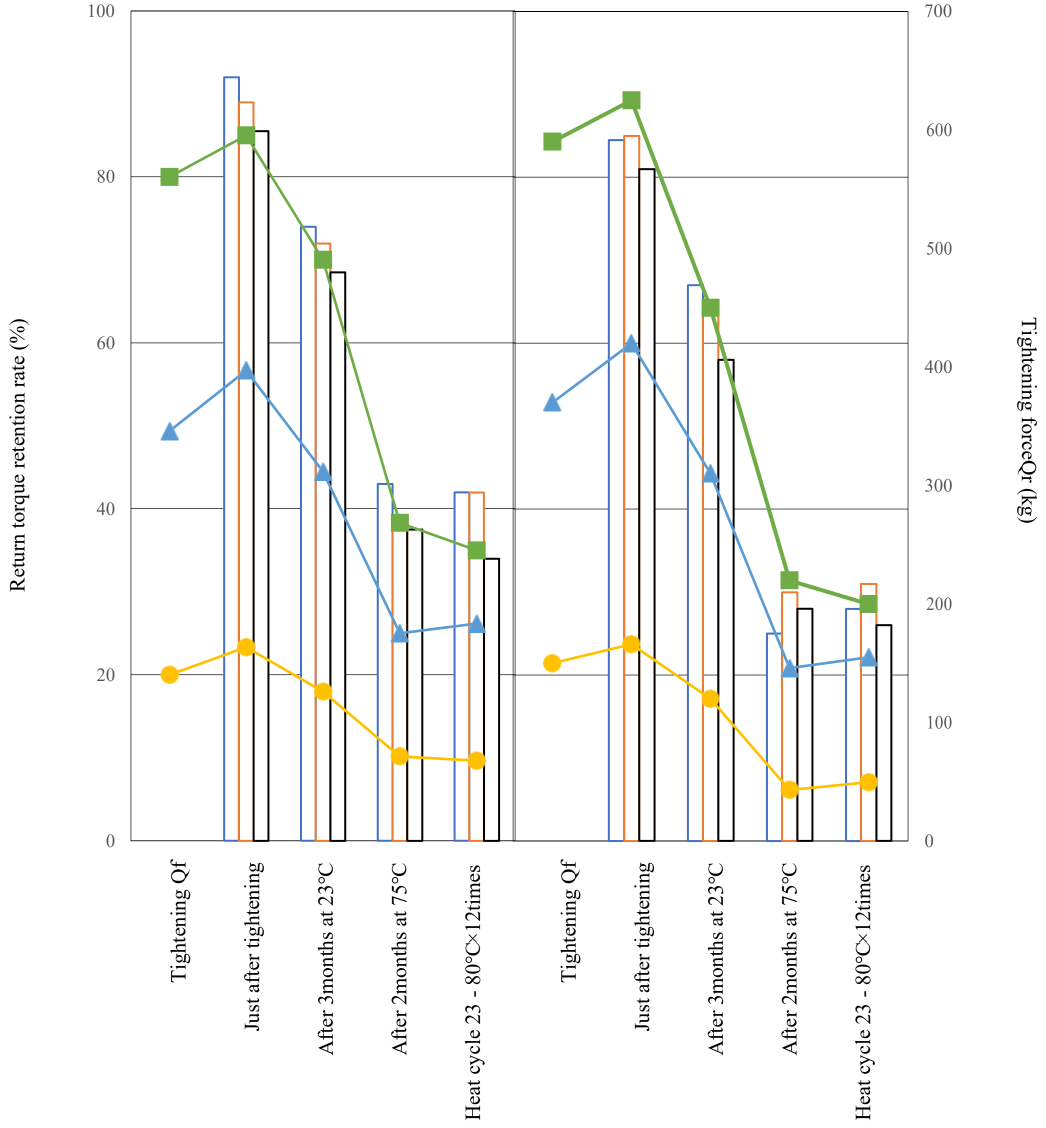

Fig. 2.3-6 M6 Return Torque Holding Rate and Tightening Force
after Long-term Tightening of Small Screw

2.4 Ultrasonic bonding

As shown in Table 2.4-1, ultrasonic bonding of polyacetals is considered to belong to a relatively easy, provided that attention is paid to the power of the welding machine and the design of the joint. Its application range is applicable to direct welding, rivets, inserts, etc. in addition to transfer welding.

Tests on Iupital specimens (Fig. 2.4-1) using ultrasonic bonding (transfer welding) produced the results displayed in Figures 2.4-2 and 2.4-3. These results highlight that high strength bonds are attainable with sufficient output and pressurization time. Conversely, insufficient parameters led to peeling at the weld, while optimal parameters resulted in base material fracture, indicating robust bonding.

Table 2.4-1 Ultrasonic bonding performance of plastics

◎ : Superior, ○: Good, △ : Possible

Plastics	Transmission	Direct	Rivet	Insert	State of bonding
Polystyrene GP	◎	◎	◎	◎	Good acoustic characteristics, low attenuation, and low solidification time
Polystyrene HI	◎−○	◎	◎	◎	Up to 30% gum content (transfer) GP not equivalent
AS	◎−○	◎	◎	◎	Decay, 30% greater than polystyrene (GP)
ABS	◎−○	◎	◎	◎	It is improved with glass fiber. Bonded with AS, Polystyrene, and acrylic
Polycarbonate	◎−○	◎	◎	◎	High energy is required because softening temperature is high.
					Bonding is good after drying and just after injection
Nylon	△	○	◎	◎	Glass fiber improves the bonding. Drying also improves bonding.
Polysulfone	○	○	◎	◎	
Polyacetal	○	○	◎	◎	Require high energy
Acrylic	◎−○	◎	◎	◎	Be bonded with AS,ABS.
Polyphenylene oxide	○	○	○	◎	Require high energy
Polypropylene	△	◎−○	◎	◎	Attenuation is large. Thin material is preferred.
Polyethylene	△	◎−○	◎	◎	Longer vibration time is required due to large heat conduction
Vinyl chloride (hard)	△	◎	○	○	There is possibility of being decomposed.
Acetate	△	○	○	○	Stress distribution should be uniform for those with many acetyl caps.

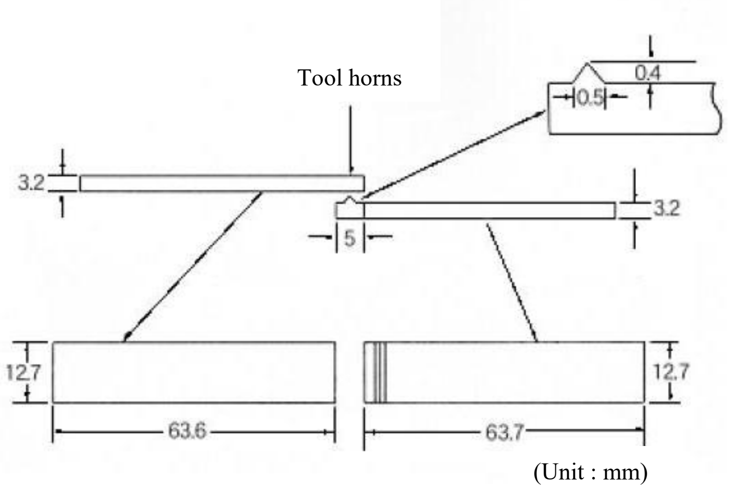

Figure 2.4-1 Ultrasonic Bonding Test Method

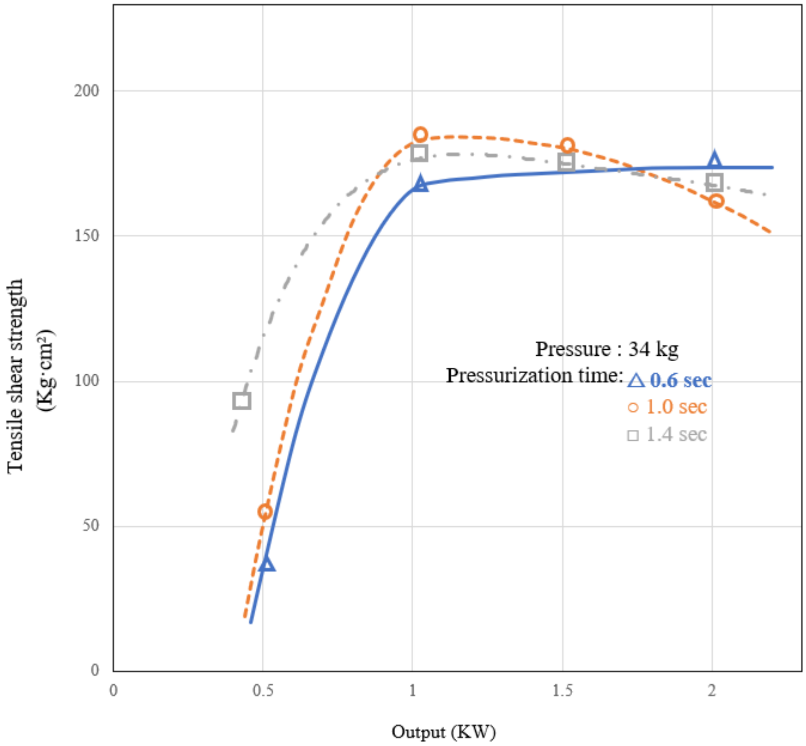

Fig. 2.4-2 Effect of output

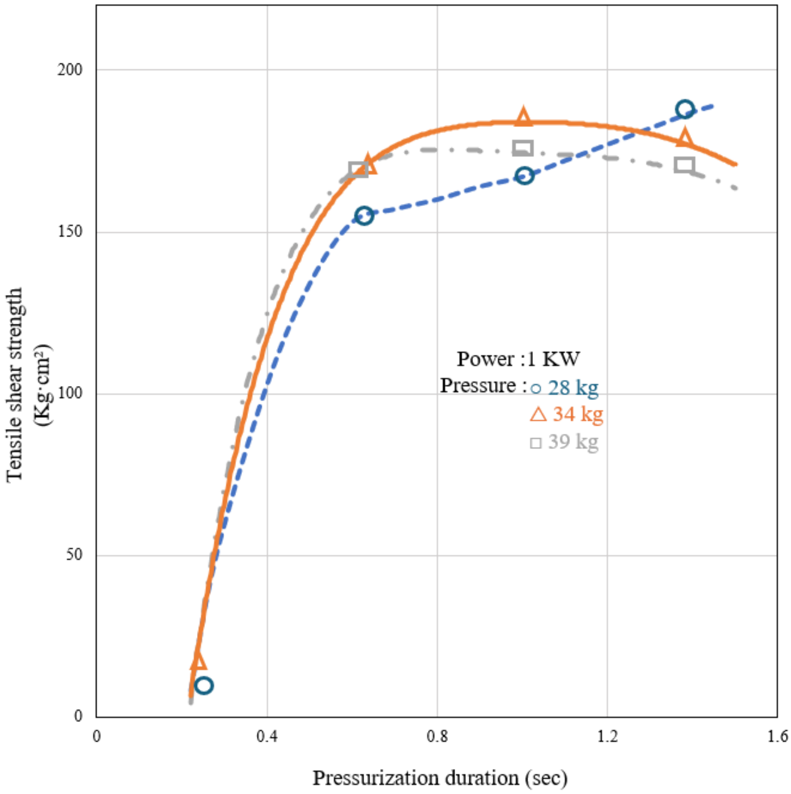

Fig. 2.4-3 Effect of pressurization time

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2.5 Adhesive bonding

Adhesive bonding of Iupital moldings was carried out in the following method.

Test piece

Size (width) 20mm× (length) 70mm

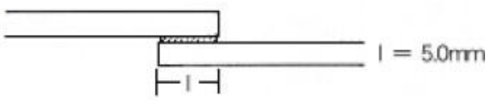
Thickness 1.0, 2.0, 3.0, 5.0, 8.0 mm

Pretreatment of the adhesive surface

Only degreasing (using acetone)
Roughening (roughening by endless polishing belt of #120)

Bonding method

Overlapping



Butt

Table 2.5-1 presents the results, indicating that cyanoacrylate or epoxy adhesives show relatively high adhesion strength with Iupital. However, due to the inherently low surface affinity of molded Iupital, chemical or physical roughening significantly improves adhesive bonding.

Table 2.5-1 Bonding of Iupital with Adhesive

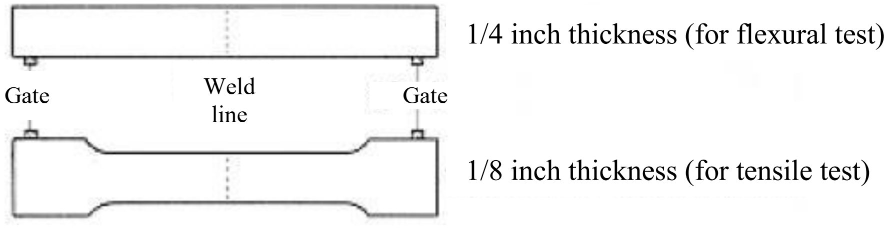
Adhesive	Treatment of surface	Bonding method				
		Overlapping*				Butt**
		Thickness of test specimen (mm)				
		1.0	2.0	3.0	5.0	8.0
Cyanoacrylate type	Non treatment	9	15	8	5	52
	Roughening #120	23	27	36	44	53
Epoxy type	Non treatment	9	15	20	18	36
	Roughening #120	19	25	28	28	57
Modified acrylics type	Non treatment	7	14	12	20	23
	Roughening #120	21	23	27	27	25
Rubber type (Chloroprene rubber)	Non treatment	12	11	8	8	10
	Roughening #120	20	22	22	19	10

* Tensile shear strength
** Tensile strength

3. Weld strength

Molded parts serving functional or structural roles often incorporate features such as open holes, screw bosses, and reinforcing ribs. Additionally, the complex flow of resin, influenced by multipoint gates and varying wall thickness, results in the formation of weld lines. These weld lines are critical areas because stress tends to concentrate there when external forces are applied, making them brittle under impact and load, and potentially weakening the overall structure. The retention ratios of tensile strength, elongation, and flexural strength in these welded areas are presented in Figure 3-1.

Test specimen and the position of weld line



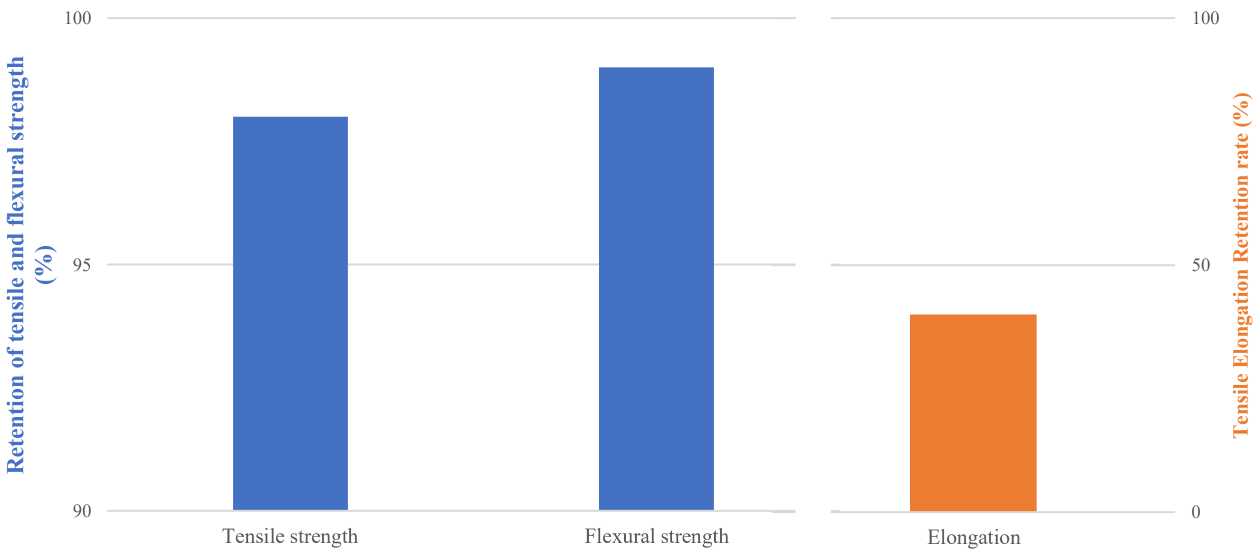


Fig. 3-1 Weld strength

4.1 Iupital' s exceptional mechanical properties, long-term durability, resistance to heat and chemicals, and outstanding frictional wear performance make it ideal for a wide range of sliding applications, notably bearings. Recognizing the slight variations in frictional wear behavior between journal and thrust bearings, the fundamental concepts of bearing design will be discussed. Bearing bore diameter (bearing clearance)

. While journal bearing clearance (δ) depends on operating conditions, a clearance of 5/1000 to 8/1000 times the shaft diameter is generally sufficient for typical use within normal temperature ranges.

$$\boldsymbol{\delta_1 = \varphi_1 \cdot ds}$$

φ_1 =5/1000～8/1000, :Shaft diameter ds

However, if rotational friction between the bearing and the metal shaft generates significant heat, causing the bearing or the operating environment to reach high temperatures, the clearance must be adjusted to account for these thermal changes. The calculation for this adjusted clearance is as follows.

$$\boldsymbol{\delta_2 = (\varphi_1 - \varphi_2 + \varphi_3 \pm \varphi_4 \pm \varphi_5)\ ds}$$

φ_2: Difference in linear expansion coefficient between bearing and shaft

$\varphi_2 = (\alpha P - \alpha M)\Delta T$

$\alpha P, \alpha M$:Linear expansion rates of resin(P) and metal(M),

Material	linear expansion coefficient（$\times 10^{-5}$cm/cm/℃）
Iupital	13.1（20℃～80℃）
Copper	1.6～2.4
Brass	1.9
Aluminum	2.4

ΔT: Differences in temperature between normal temperature and usage conditions

φ_3 : Heat shrinkage of the bearing material
High-temperature exposure promotes crystallization in the bearing, causing it to shrink. The amount of shrinkage is affected by the molded part's thickness and the molding conditions.. It is sufficient to expect φ_{3a} as 0.1~ 0.5%.

φ_4: Dimensional variation due to molding
Dimensional variation is expected φ_4 as ±0.05% compared with reference.

φ_5 : Dimensional change due to lubricating oil, etc.
Since there are cases where it expands or contracts depending on the type of lubricating oil, changes of φ_5 =±0.2% are considered.

While the linear expansion mismatch (φ_2) between the bearing and shaft and the thermal shrinkage of the bearing (φ_3) significantly alter clearance at high temperatures, dimensional changes due to lubricants (φ_5) and manufacturing variations (φ_4) have a comparatively negligible effect.

In the case of press-fitting Iupital bearing into a metal housing, the bearing bore diameter should be increased in anticipation of a decrease in the bearing bore diameter.
In this case,

$$\varphi_6 = \frac{2k}{K(1-\upsilon) + (1+\upsilon)} \cdot I$$

$$K = \frac{Bearing\ outer\ diameter}{Bearing\ inner\ diameter}$$

υ: Poisson's ratio (0.35) for Iupital standard grade
I: Interference when press-fitting

And then represented as follows.

$$\delta_3 = (\varphi_1 - \varphi_2 + \varphi_3 \pm \varphi_4 \pm \varphi_5 + \varphi_6)\ ds$$

4.2 Bearing outer diameter (bearing wall thickness)

Bearing wall thickness is generally about 1.00～1.25mm considering frictional heat generation (critical PV), dimensional accuracy of molded products, strength, etc.
i) Tightening allowance when press-fitting a bearing into a metal housing
The compressive stress σ of the bearing due to press-fitting shall be less than or equal to the max. allowable compressive stress 1050kg/c m2 of Iupital.

$$\sigma = \frac{2pk^2}{k^2 - 1}$$

σ: Compressive Stress (kg/cm^2)
p: Contact surface pressure (kg/cm^2) between the metal-housing and the bearing.

ii) Relationship between contact surface pressure and interference

$$\frac{I}{2r_2} = \frac{p}{E\left[\frac{k^2+1}{k^2-1} - \upsilon\right]}$$

$2r_2$: Inner diameter of the metal housing
E : Apparent modulus of elasticity at practical temperature and maximum operating time

The indentation allowance obtained here is the value in the actual use condition. Therefore, it is necessary to consider the amount of linear expansion and heating shrinkage of the bearing.

4.3 Bearing length

The bearing length is recommended to be equivalent to the bearing diameter in consideration of frictional heat generated per piece due to eccentricity and wear. The equivalent compressive stress applied to the bearing (σ c) is expressed by the following equation

$$\sigma C = \frac{W}{2r_2 \cdot l}$$

W : Vertical load applied to the bearing
$2r_2$: Bearing outside diameter
l : Bearing length

4.4 Bearing durability

Long-term endurance of bearings is regulated by the wear rate below the critical PV. The specific wear amount of the bearing also varies depending on the clearance of the bearing shaft, etc. Fig. 4.4-1, 4.4-2 and 4.4-3 show the frictional modulus, limit PV value, and specific wear when using a 10mmφ steel shaft.

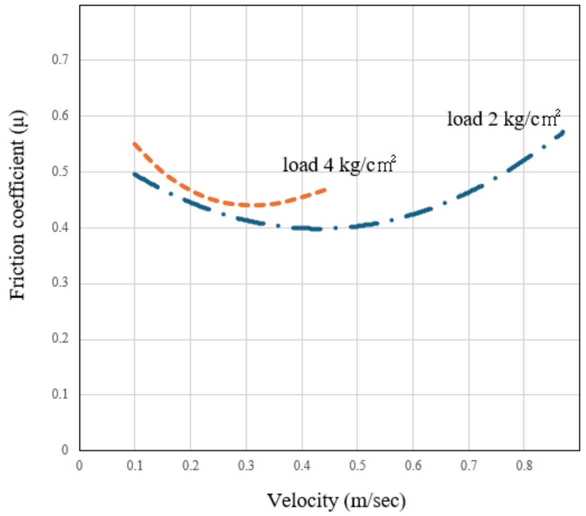


Fig. 4.4-1 Effect of load and speed on friction coefficient (vs. steel)

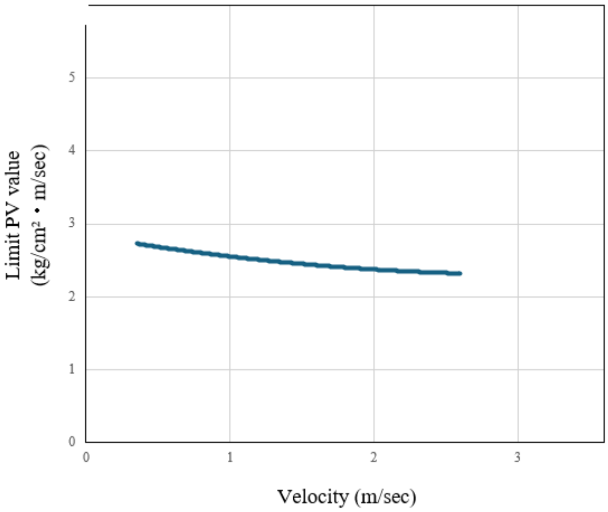


Fig. 4.4-2 Effect of velocity on limit PV value (vs. steel)

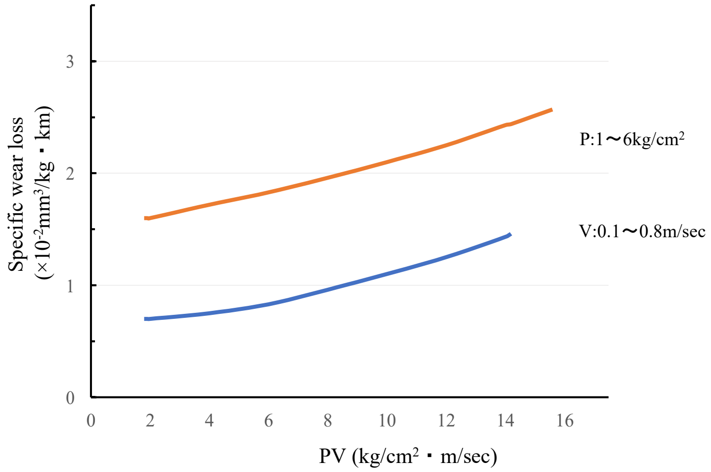


Fig. 4.4-3 Relation between specific wear rate and PV value in bearings (vs. steel)