5. Gear design and strength

Lupital has good strength, durability, wear resistance, and chemical resistance, so can be used to each gear. Gear wreck will happen because of its tooth fatigue and tooth surface wear, so strength design from both side is necessary.

5.1 Gear design

5.1.1 Dedendum strength

Lewis formula (1) is generally employed for flexural stress on dedendum.

\[ W = S \cdot b \cdot m \cdot (y') \]

\[ S : \text{Flexural stress on dedendum (kg/mm)²} \]

\[ m : \text{Module (mm)} \]

\[ b : \text{Face width (mm)} \]

\[ (y') : \text{Tooth form modulus (see table 5.1.1-1)} \]

\[ W : \text{Pitch circumferential tangent load (kg)} \]

Table 5.1.1-1 Tooth form modulus of spur gear

<table>
<thead>
<tr>
<th>Teeth number</th>
<th>y'(y')</th>
<th>z</th>
<th>y'(y')</th>
<th>Teeth number</th>
<th>y'(y')</th>
<th>z</th>
<th>y'(y')</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>0.277</td>
<td>0.415</td>
<td>0.433</td>
<td>0.713</td>
<td>12</td>
<td>0.237</td>
<td>0.355</td>
</tr>
<tr>
<td>13</td>
<td>0.292</td>
<td>0.443</td>
<td>0.443</td>
<td>0.735</td>
<td>13</td>
<td>0.249</td>
<td>0.377</td>
</tr>
<tr>
<td>14</td>
<td>0.308</td>
<td>0.468</td>
<td>0.454</td>
<td>0.757</td>
<td>14</td>
<td>0.261</td>
<td>0.399</td>
</tr>
<tr>
<td>15</td>
<td>0.319</td>
<td>0.490</td>
<td>0.464</td>
<td>0.779</td>
<td>15</td>
<td>0.270</td>
<td>0.415</td>
</tr>
<tr>
<td>16</td>
<td>0.325</td>
<td>0.503</td>
<td>0.474</td>
<td>0.801</td>
<td>16</td>
<td>0.279</td>
<td>0.430</td>
</tr>
<tr>
<td>17</td>
<td>0.330</td>
<td>0.512</td>
<td></td>
<td></td>
<td>17</td>
<td>0.288</td>
<td>0.446</td>
</tr>
<tr>
<td>18</td>
<td>0.335</td>
<td>0.522</td>
<td></td>
<td></td>
<td>18</td>
<td>0.293</td>
<td>0.459</td>
</tr>
<tr>
<td>19</td>
<td>0.340</td>
<td>0.534</td>
<td></td>
<td></td>
<td>19</td>
<td>0.299</td>
<td>0.471</td>
</tr>
<tr>
<td>20</td>
<td>0.346</td>
<td>0.543</td>
<td></td>
<td></td>
<td>20</td>
<td>0.305</td>
<td>0.481</td>
</tr>
<tr>
<td>21</td>
<td>0.352</td>
<td>0.553</td>
<td></td>
<td></td>
<td>21</td>
<td>0.311</td>
<td>0.490</td>
</tr>
<tr>
<td>22</td>
<td>0.354</td>
<td>0.559</td>
<td></td>
<td></td>
<td>22</td>
<td>0.313</td>
<td>0.496</td>
</tr>
<tr>
<td>23</td>
<td>0.359</td>
<td>0.572</td>
<td></td>
<td></td>
<td>23</td>
<td>0.318</td>
<td>0.509</td>
</tr>
<tr>
<td>26</td>
<td>0.367</td>
<td>0.587</td>
<td></td>
<td></td>
<td>26</td>
<td>0.327</td>
<td>0.522</td>
</tr>
<tr>
<td>28</td>
<td>0.372</td>
<td>0.597</td>
<td></td>
<td></td>
<td>28</td>
<td>0.332</td>
<td>0.534</td>
</tr>
<tr>
<td>30</td>
<td>0.377</td>
<td>0.606</td>
<td></td>
<td></td>
<td>30</td>
<td>0.334</td>
<td>0.540</td>
</tr>
<tr>
<td>34</td>
<td>0.388</td>
<td>0.628</td>
<td></td>
<td></td>
<td>34</td>
<td>0.342</td>
<td>0.553</td>
</tr>
<tr>
<td>38</td>
<td>0.400</td>
<td>0.650</td>
<td></td>
<td></td>
<td>38</td>
<td>0.347</td>
<td>0.565</td>
</tr>
<tr>
<td>43</td>
<td>0.411</td>
<td>0.672</td>
<td></td>
<td></td>
<td>43</td>
<td>0.352</td>
<td>0.575</td>
</tr>
<tr>
<td>50</td>
<td>0.422</td>
<td>0.694</td>
<td></td>
<td></td>
<td>50</td>
<td>0.357</td>
<td>0.587</td>
</tr>
</tbody>
</table>
5.1.2 Tooth surface strength

Damage phenomenon like pitching and wear will occur on tooth surface, and Hertz formula (2) is generally employed.

\[ W = \sigma_a b d_1 \left( \frac{2Z_1}{Z_1 + Z_2} \right) \left( \frac{1}{E_1} + \frac{1}{E_2} \right) \]

\[ \frac{\sin 2\alpha}{2.3} \left( \frac{2Z_1}{Z_1 + Z_2} \right) \left( \frac{1}{E_1} + \frac{1}{E_2} \right) \]

\( W \): Pitch circumferential tangent load
\( b \): Face width
\( d_1 \): Gear pitch circle diameter
\( \alpha \): Meshing pressure
\( Z_1 \): Gear teeth number
\( Z_2 \): Pinion teeth number
\( E_1 \): Gear longitudinal elastic modulus
\( E_2 \): Pinion longitudinal elastic modulus
\( \sigma_a \): Allowable compressive stress

5.2 Tooth fatigue strength and surface pressure strength

Tooth fatigue failure, flexural stress that led to wear damage, and surface pressure will change by the difference of operational aspect.

Following are some factors that effect to tooth duration

1) Actual usage temperature
2) Existence of lubricity
3) Gear material used for power transmission
4) Operational aspect (continuous or intermittent operation)
5) Power transmission speed
6) Wear property of contacting face
7) Meshing ratio

so, overall consideration is necessary.

Figure 5.2-1 and 5.2-2 indicate gear fatigue endurance, and surface pressure strength.

Gear strength S-N curve

Figure 5.2-1  Relationship of gear strength and cycle

Figure 5.2-2  Relationship of gear strength and cycle
6. Joint

6.1 Metal insert

There is method that insert when molding, and method that insert after molding, but in this section, former insert method is going to be stated.

Result of inserting by brass insert clasp is indicated in Figure 6.1-2 to 6.1-4. The following will be obvious from these results.

1) Thickness ratio, pullout force, and rotary torque around insert clasp will become upward convex curve, and indicates peak in thickness ratio of about 2.0. This will decrease by material mechanical holding force degradation on the small thickness ratio side, and by sink effect of thickness direction on the bigger side.

2) Pullout force and rotary torque value will increase by thermal process. This is considered as heat shrinkage effect.

3) Holding force will widely increase by placing knurling groove.

4) Figure 6.1-5 indicates stress around insert clasp, calculated from pullout force value. This is calculated from next formula.

\[ \sigma_{\text{max}} = \frac{FW}{\pi DL\mu} \]

- \( \sigma_{\text{max}} \): Maximum pullout stress (kg/cm²)
- \( F \): Pullout force (kg)
- \( W \): \( k_2+1/(k_2-1) \)
- \( k \): \( D_0/D_i \) (boss outer diameter/insert clasp diameter)
- \( L \): Insert clasp length (cm)

Points to look out about lupital molding insert is crack generation around clasp. The following will be some causes of crack, so be careful.

1) Stress concentration by clasp sharp edge
2) Weld line
3) Stress increase by heat aging in usage environment

There is also a case that caused crack from knurl sharp edge weld part by thermal process in 75°C for 3,000 to 4,000
Figure 6.1-1  Insert molded product shape and insert holding force measurement method

(1) Test piece shape

![Diagram of test piece shape]

- Boss outer diameter
- Insert clasp
- Molded product
- Unit mm
- Insert diameter: Ds

(2) Measurement method

i) Pullout force (axis direction holding force)

![Diagram of pullout force measurement]

- Molded product
- Insert

ii) Rotary torque (circumferential holding force)

![Diagram of rotary torque measurement]

- Molded product
- Insert
Clasp holding condition in insert molding (insert clasp 7 mm φ × 13 mm L brass)

Figure 6.1-2 Insert clasp pullout force without knurl

Figure 6.1-3 Insert clasp pullout force with knurl

Figure 6.1-4 Insert clasp rotary torque without knurl

Figure 6.1-5 Stress in each thickness ratio
6.2 Fastening by self tap screw

Iupital self tap screw property is examined by changing prepared hole diameter (hang-up rate), boss outer diameter, and screw depth, of 3mm φ self tap screw, using Iupital test piece indicated in Figure 6.2-1. Hang-up rate here is calculated as below, though there is no accurate definition for self tap screw.

\[ \text{Hang-up rate (\%)} = \frac{D(\text{Male screw outer diameter}) - d1(\text{Prepared hole diameter})}{D(\text{Male screw outer diameter}) - D1(\text{Male screw root diameter})} \]

Result is as indicated in Figure 6.2-2～6.2-5. Followings became obvious from the result.
1) Bigger the hang-up rate and screw depth is, bigger the screw pullout force and driving torque is.
2) If boss thickness become thicker, and the hang-up rate is big, pullout force and breakdown torque will be bigger.
3) Thermal process and heat cycle process will progress the breakdown torque and degrade loosening torque.

When fastening Iupital molded product by self tap screw, greater hang-up rate will increase the breakdown torque and pullout force, but driving torque will be bigger, and workability will be worse. Make the screw depth deeper if want to increase breakdown torque and pullout force without worsening workability. Boss part thickness should be more than 1/2 of screw outer diameter, but if it is too thick, sink will generate and degrades hang-up rate, so be careful.

(1) Test piece shape

![Diagram of test piece shape](image1)

- \(d1\): Prepared hole diameter
- \(d2\): Boss outer diameter
- \(l\): Screw depth

Unit mm

(2) Measurement method

- Pullout force measurement (by autograph)
- Torque measurement (by torque driver)

Figure 6.2-1 Self tap screw fastening
(1) Driving torque and breakdown torque

(screw: outer diameter 3mm cross-recessed tapping screw, with two types of end groove. By JIS B1122)

<table>
<thead>
<tr>
<th>Boss thickness t=1.5mm</th>
<th>Hang-up rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>△ ▲ 17 - 31 %</td>
<td></td>
</tr>
<tr>
<td>○  44 - 59 %</td>
<td></td>
</tr>
<tr>
<td>□  67 - 81 %</td>
<td></td>
</tr>
</tbody>
</table>

(2) Screw pullout force

Figure 6.2-2 Fastening screw depth by self tap screw
(1) Driving torque and breakdown torque  
(screw: outer diameter 3mm cross-recessed tapping screw, with two types of end groove. By JIS B1122)

![Graph showing driving torque and breakdown torque](image)

> Prepared hole diameter (Boss inner diameter) (mm)

(2) Screw pullout force

![Graph showing screw pullout force](image)

> Prepared hole diameter (Boss inner diameter) (mm)

Figure 6.2-3 Effect of fastening prepared hole diameter (hang-up rate) by self tap screw
(1) Driving torque and breakdown torque

(screw: outer diameter 3mm cross-recessed tapping screw, with two types of end groove. By JIS B1122)

<table>
<thead>
<tr>
<th>Screw depth</th>
<th>Hang-up rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>l = 2mm</td>
<td>△ 17 – 31%</td>
</tr>
<tr>
<td></td>
<td>○ 44 – 59%</td>
</tr>
<tr>
<td></td>
<td>□ 67 – 81%</td>
</tr>
</tbody>
</table>

Driving torque (white)
Breakdown torque (black)

<table>
<thead>
<tr>
<th>Screw depth</th>
<th>Hang-up rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>l = 3mm</td>
<td>△ 17 – 31%</td>
</tr>
<tr>
<td></td>
<td>○ 44 – 59%</td>
</tr>
<tr>
<td></td>
<td>□ 67 – 81%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Screw depth</th>
<th>Hang-up rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>l = 4.5mm</td>
<td>△ 17 – 31%</td>
</tr>
<tr>
<td></td>
<td>○ 44 – 59%</td>
</tr>
<tr>
<td></td>
<td>□ 67 – 81%</td>
</tr>
</tbody>
</table>

(2) Pullout force of screw

Figure 6.2-4 Effect of fastening boss thickness by self tap screw
Figure 6.2-5  Long term fastening test of self tap screw

Hang-up rate (prepared hole diameter)  two types screw M3 with end groove JIS B1122 screw depth 3.0mm

Breakdown torque

Fastening torque half of Breakdown torque

Loosening torque

Pullout force
6.3 Fastening by metal machine screw

Change in loosening torque and fastening force after Iupital molded product fastened by metal machine screw as in Figure 6.3-1, is examined.

Fastening force $Q$ generated on screw is calculated from torque $T$ by following formula.

Here indicates relationship of fastening torque $T_f$ and fastening force $Q_f$ when the code is $+$, and relationship of loosening torque $T_r$ and fastening force $Q_r$ when the code is $-$.  

$d_2$: effective diameter of screw  
$\mu$: friction coefficient of intermeshed screw thread (worked out as 0.20)  
$\theta$: screw thread angle  

$$\tan \rho = \mu \cos \frac{\theta}{2}$$

$P$: pitch  
$\beta$: lead angle of screw  
$\mu_n$: friction coefficient of bearing surface (worked out as 0.15)

$$dn = \text{average diameter of bearing surface } \left( \frac{B + d^2}{2} \right)$$

Figure 6.3-3～6.3-6 indicates result. As known from this result, loosening torque and fastening force will be decreased by stress relaxation after long term left. This tendency is especially noticeable under high temperature. Consequently, spring washer or other method will be necessary if the looseness is being problem. On the other hand, there was no cracks by thermal process or heat cycle process, around Iupital fastened part.
Fastening force will be insufficient if the fastening torque is too high, because it will cause deformation in the fastened part. It is safe if the fastening torque is set within ±20% from the standard value shown in Table 6.3-1, and tighten if there is a possibility to get loose, and loosen for better workability.

Table 6.3-1  Standard fastening torque of machine screw

<table>
<thead>
<tr>
<th>Nominal designation of thread</th>
<th>M3</th>
<th>M4</th>
<th>M5</th>
<th>M6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard fastening torque kgf cm</td>
<td>7.5</td>
<td>20</td>
<td>35</td>
<td>50</td>
</tr>
</tbody>
</table>

Fastening force will be insufficient if the fastening torque is too high, because it will cause deformation in the fastened part. It is safe if the fastening torque is set within ±20% from the standard value shown in Table 6.3-1, and tighten if there is a possibility to get loose, and loosen for better workability.

Figure 6.3-3  Loosening torque retention rate and fastening force of M3 machine screw after long term fastening
fasten in torque 10kgf cm, loosening torque after process is indicated as pullout force (Qr) is indicated as pullout force (Qr) is indicated as
fasten in torque 20kgf cm, loosening torque after process is indicated as pullout force (Qr) is indicated as pullout force (Qr) is indicated as
fasten in torque 30kgf cm, loosening torque after process is indicated as pullout force (Qr) is indicated as pullout force (Qr) is indicated as

Figure 6.3-4  Loosening torque retention rate and fastening force of M4 machine screw after long term fastening

Figure 6.3-5  Loosening torque retention rate and fastening force of M5 machine screw after long term fastening
fasten in torque $20\text{kgf} \cdot \text{cm}$, loosening torque after process is indicated as $\text{pullout force (Qr)}$ is indicated as $50\text{kgf} \cdot \text{cm}$, loosening torque after process is indicated as $\text{pullout force (Qr)}$ is indicated as $80\text{kgf} \cdot \text{cm}$, loosening torque after process is indicated as $\text{pullout force (Qr)}$ is indicated as

Figure 6.3-6  Loosening torque retention rate and fastening force of M6 machine screw after long term fastening
As shown in Table 6.4-1, polyacetal ultrasonic jointing is relatively easy if took care of deposition machine power and joining area design. It is applicable to not only deposition transmitting, but also direct deposition, rivet, and insert.

As a lupital ultrasonic jointing (deposition transmitting), test was conducted by using test piece like indicated in Figure 6.4-1. Result is as shown in Figure 6.4-2 and 6.4-3. As shown in this result, high strength can be gained if there is enough output power and pressure time. Also, detachment of deposition surface is indicated at low strength side, but maternal destruction is indicated at high strength side, which can be considered sufficient.

<table>
<thead>
<tr>
<th>Plastics</th>
<th>Transmittance</th>
<th>Direct</th>
<th>Rivet</th>
<th>Insert</th>
<th>Deposition condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>PolystyreneGP</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Good acoustic property, less depression, great deposition, short solidification time</td>
</tr>
<tr>
<td>PolystyreneHT</td>
<td>Excellent→Great</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Rubber content up to 30% (transmission) conformed to GP</td>
</tr>
<tr>
<td>AS</td>
<td>Excellent→Great</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Excellent</td>
<td>30% more depression compared to Polystyrene (GP)</td>
</tr>
<tr>
<td>ABS</td>
<td>Excellent→Great</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Reformed by glass (15%) Deposited with AS, Polystyrene, and Acrylic</td>
</tr>
<tr>
<td>Polycarbonate</td>
<td>Excellent→Great</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Excellent</td>
<td>High energy required because of high softening temperature, good deposition with article soon after drying or injection</td>
</tr>
<tr>
<td>Nylon</td>
<td>Good</td>
<td>Great</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Better deposition property with glass Better deposition property by drying</td>
</tr>
<tr>
<td>Polysulfone</td>
<td>Great</td>
<td>Great</td>
<td>Excellent</td>
<td>Excellent</td>
<td>High energy required</td>
</tr>
<tr>
<td>Polyacetal</td>
<td>Great</td>
<td>Great</td>
<td>Excellent</td>
<td>Excellent</td>
<td>High energy required</td>
</tr>
<tr>
<td>Acrylic</td>
<td>Excellent→Great</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Deposited with AS and ABS</td>
</tr>
<tr>
<td>Polyphenylene oxide</td>
<td>Great</td>
<td>Great</td>
<td>Great</td>
<td>Excellent</td>
<td>High energy required</td>
</tr>
<tr>
<td>Polypropylene</td>
<td>Good</td>
<td>Excellent→Great</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Big depression, relatively thin (transmission)</td>
</tr>
<tr>
<td>Polyethylene</td>
<td>Good</td>
<td>Excellent→Great</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Longer vibration time because of large thermal conduction</td>
</tr>
<tr>
<td>Chloroethylene (hard)</td>
<td>Good</td>
<td>Excellent</td>
<td>Great</td>
<td>Great</td>
<td>Decompose by case</td>
</tr>
<tr>
<td>Acetate</td>
<td>Good</td>
<td>Great</td>
<td>Great</td>
<td>Great</td>
<td>Equalize stress distribution if many acetyl group</td>
</tr>
</tbody>
</table>
Figure 6.4-1  Ultrasonic deposition testing method
Figure 6.4-2  Effect of output power

Figure 6.4-3  Effect of pressure time
6.5 Adhesion by bond

Lupital bond adhesion conducted in following method.
Test piece
Size (width) 20mm × (length) 70mm
Thickness 1.0, 2.0, 3.0, 5.0, 8.0 mm

Preparation of bonding plane
Degreasing only (acetone used)
Roughened (roughened by #120 endless polishing belt)

Joining method
Superposition

![Test piece diagram]

Collation

Result is indicated in Table 6.5-1. As shown in this table, cyanoacrylate and epoxy adhesion bond is relatively good for Lupital, if joining Lupital to Lupital. On the other hand, Lupital molded product surface lacks affinity, so adhesion strength will rise widely by chemically or physically roughening.

**Table 6.5-1** Lupital joining by adhesion bond

<table>
<thead>
<tr>
<th>Bond</th>
<th>Bonding plane process</th>
<th>Joining method</th>
<th>Test piece thickness mm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Superposition</td>
<td>1.0 2.0 3.0 5.0 8.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Collation**</td>
<td></td>
</tr>
<tr>
<td>Cyanoacrylate</td>
<td>Unprocessed</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Roughening #120</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Epoxy</td>
<td>Unprocessed</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Roughening #120</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Modified acrylic</td>
<td>Unprocessed</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Roughening #120</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rubber</td>
<td>Unprocessed</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(chloroprene rubber)</td>
<td>Roughening #120</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Tensile shear strength
** Tensile strength
Molded products which are used as functional part or structural part, must have thread fastening hole, boss, and rib for reinforcement. Furthermore, resin flow will be complex by multipoint gate and thickness distribution, and will cause weld. It will cause stress concentration at external force loaded part, and will become weaker against impact and load, and could even end up with strength deterioration, so be careful.

Weld part tensile strength, elongation, and flexural strength retention rate is indicated in Figure 7-1.