[45] CT-FEM Opera ⅲ (Stress analysis)

English version

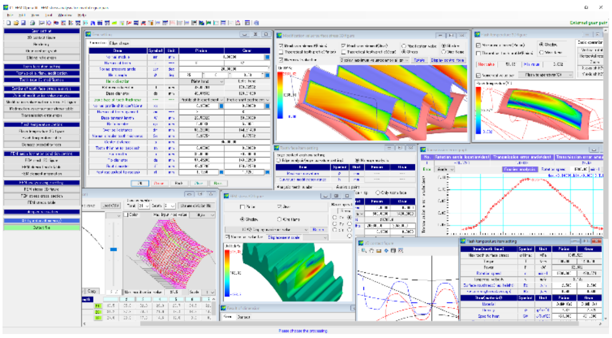
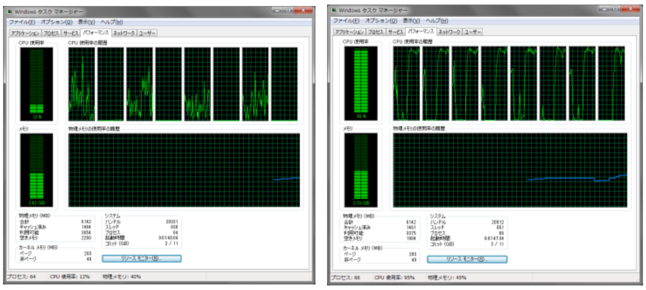


Fig.45.1 CT-FEM Opera ⅲ

45.1 Abstract

The CT-FEM Opera which was developed in 2014 is the software which has a lot of results, doing much verification. In this time, we developed new **CT-FEM Opera ⅲ** (includes a parallel processing feature), doing based on the CT-FEM Opera. For example, when analyzing a helical gear (m_n=2, z_1=z_2=20, α=20°, β=11°, b_1=b_2=10) in 3D-FEM (elements =18335, nods = 29638), the computing time of the CT-FEM Opera is 105 seconds but in **CT-FEM Opera ⅲ**, it is 13.7 seconds (Microsoft Surface Pro3, CPU: Intel® Core™ i7-4650U, Memory, 8.0GB).



(a) not parallel processing (b) parallel processing

Fig.45.2 CPU system operating status（Task Manager）

The **CT-FEM Opera ⅲ** enriches a tooth surface analysis. The contents can be computed in the flash temperature, the friction coefficient, the oil film thickness, the transmission error analysis, Fourier analyses, scuffing probability and then the lifetime time, too. Also, it is adding an edge contact analysis and a best tooth surface formation analysis (tooth surface stress minimum value), too. Therefore, the damage by the trochoid interference and the noise can do the tooth surface retouch which is proper for the occurring gear.

Then, the stress change at the rotation angle can be observed by the animated feature. Therefore, because the stress distribution phenomenon can be easily grasped when analyzing by the specification of the gear which the damage occurred to, it is very valid with the improvement of the present situation gear and the explanation to the user.

Moreover, the beginner can use easily because the explanation is displayed by pushing [F1] key if there are unclear contents when using software. Fig.45.1 shows the whole screen.

See by all means because the analysis and the transmission error analysis of the tooth surface damage experiment are shown to the appendix [I], [J].

45.2 Software structure

The structure of **CT-FEM Opera ⅲ** is shown in Table 45.1. ○ in the table is included in the basic software, and ◎ is optional. Applicable gear: involute spur and helical gear (external gear, internal gear)

Table 45.1 software structure

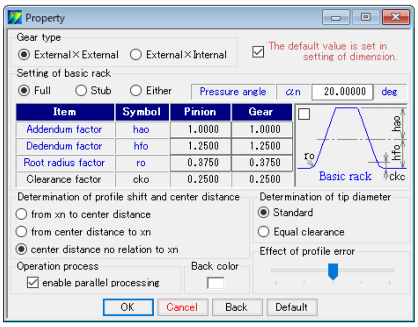
Item	Structure
⟨1⟩Basic rack	○
⟨2⟩Gear dimension	○
⟨3⟩Meshing drawing	○
⟨4⟩Tooth modification	○
⟨5⟩Tooth surface stress distribution (3D)	○
⟨6⟩Tooth surface evaluation (1) friction coefficient, oil film thickness, calorific potential, Power loss PV value, PVT value	○
⟨7⟩Scuffing probability of occurrence (1)	○
⟨8⟩Abrasion probability of occurrence (1)	○
⟨9⟩Life time (1)	○
⟨10⟩Power loss (1)	○
⟨11⟩3D-FEM	○
⟨12⟩ Edge contact analysis	◎
⟨13⟩Transmission analysis, Fourier analyses, CSV	◎
⟨14⟩Internal gear	◎
⟨15⟩Best tooth surface modification	◎
⟨16⟩Tooth profile data(3D-IGES)	◎

(1) Doesn't support a plastic gear

45.3 Property (Basic rack)

A setting screen is shown to Fig.45.3.

- Gear combination : external × external, external × internal
- Basic rack : standard, low, special
- tooth tip circle decision : normal, equal clearance
- center distance and shift coefficient
- The switch which makes parallel processing valid
- The switch to consider the influence of the profile deviation



Gear type
● External×External ○ External×Internal
☑ The default value is set in setting of dimension.

Setting of basic rack
● Full ○ Stub ○ Either
Pressure angle αn 20.00000 deg

Item	Symbol	Pinion	Gear
Addendum factor	hao	1.0000	1.0000
Dedendum factor	hfo	1.2500	1.2500
Root radius factor	ro	0.3750	0.3750
Clearance factor	cko	0.2500	0.2500

Determination of profile shift and center distance
○ from xn to center distance
○ from center distance to xn
● center distance no relation to xn

Determination of tip diameter
● Standard
○ Equal clearance

Effect of profile error

Operation process
☑ enable parallel processing

Back color

Fig.45.3 property (basic rack)

45.4 Gear dimension

Gear dimension calculates parts dimensions, contact ratio, sliding ratio, tooth thickness and so on. The gear with undercut determines the contact rate based on the TIF (True Involute Form) diameter. If tooth tip is rounded, R and C is considered in contact ratio.

(1) center distance and shift coefficient have the following 3 relationships.

<1> shift coefficient is given to pinion and gear to determine center distance.

<2> based on center distance, shift coefficient of each gear is determined.

<3> center distance is set, regardless of shift coefficient.

(2) shift coefficient is set per following 4 types;

<1> directly enter shift coefficient

<2> based on split tooth thickness, shift coefficient is set

<3> based on over pin dimension, shift coefficient is set

<4> based on arc tooth thickness, shift coefficient is set

Dimension setup screen is shown in Fig.45.4 Shift coefficient can be set by tooth thickness. See Fig.45.6 for dimension result.

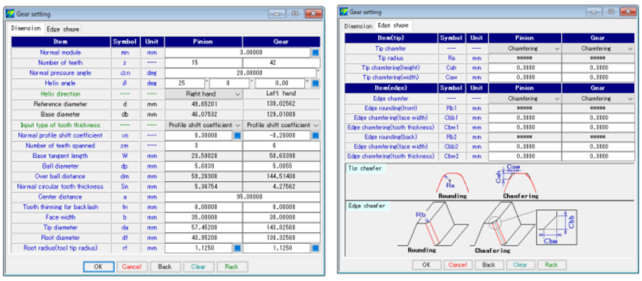
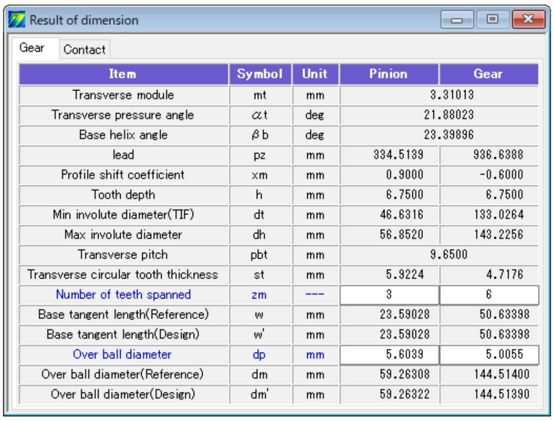
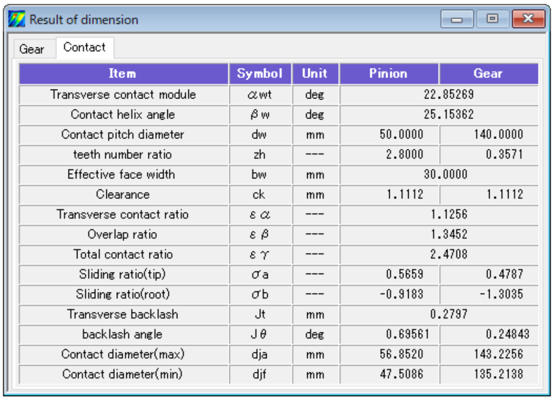

(a) gear dimension (b) chamfering

Fig.45.4 gear specification



Item	Symbol	Unit	Pinion	Gear
Transverse module	mt	mm	3.31013	
Transverse pressure angle	αt	deg	21.88023	
Base helix angle	βb	deg	23.39896	
lead	pz	mm	334.5139	936.6388
Profile shift coefficient	xm	mm	0.9000	-0.6000
Tooth depth	h	mm	6.7500	6.7500
Min involute diameter(TIF)	dt	mm	46.6316	133.0264
Max involute diameter	dh	mm	56.8520	143.2256
Transverse pitch	pbt	mm	9.6500	
Transverse circular tooth thickness	st	mm	5.9224	4.7176
Number of teeth spanned	zm	---	3	6
Base tangent length(Reference)	w	mm	23.59028	50.63398
Base tangent length(Design)	w'	mm	23.59028	50.63398
Over ball diameter	dp	mm	5.6039	5.0055
Over ball diameter(Reference)	dm	mm	59.26308	144.51400
Over ball diameter(Design)	dm'	mm	59.26322	144.51390

Fig.45.5 dimension result-1

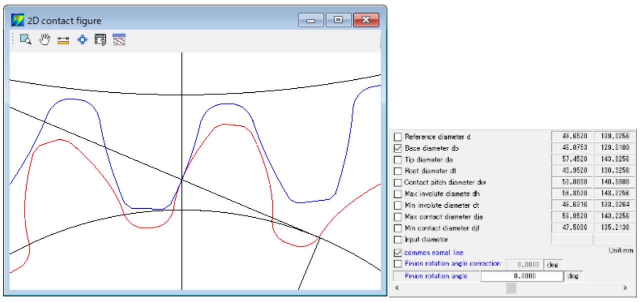


Item	Symbol	Unit	Pinion	Gear
Transverse contact module	αwt	deg	22.85269	
Contact helix angle	βw	deg	25.15362	
Contact pitch diameter	dw	mm	50.0000	140.0000
teeth number ratio	zh	---	2.8000	0.3571
Effective face width	bw	mm	30.0000	
Clearance	ck	mm	1.1112	1.1112
Transverse contact ratio	εα	---	1.1256	
Overlap ratio	εβ	---	1.3452	
Total contact ratio	εγ	---	2.4708	
Sliding ratio(tip)	σa	---	0.5659	0.4787
Sliding ratio(root)	σb	---	-0.9183	-1.3035
Transverse backlash	Jt	mm	0.2797	
backlash angle	Jθ	deg	0.69561	0.24843
Contact diameter(max)	dja	mm	56.8520	143.2256
Contact diameter(min)	djf	mm	47.5086	135.2138

Fig.45.6 dimension result-2

45.5 Tooth profile and rendering

Meshing drawing is shown in Fig.45.7. As shown in support form, zoom, distance measurement, R-measurement, diameter, involute modification, line of action, display and rotation function are available. And a rendering is shown in Fig.45.8.



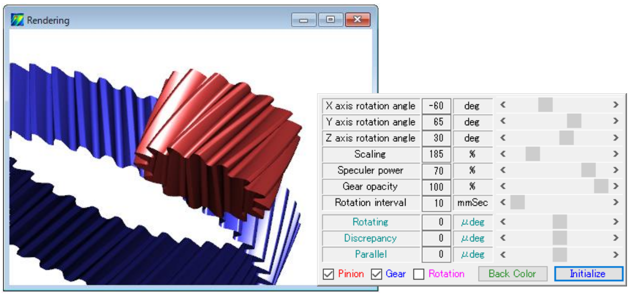
☐ Reference diameter d	49.6520	139.0256
☑ Base diameter db	46.0753	129.0109
☐ Tip diameter da	57.4520	143.0256
☐ Root diameter df	43.9520	130.3256
☐ Contact pitch diameter dw	50.0000	140.0000
☐ Max involute diamete dh	56.8520	143.2256
☐ Min involute diameter dt	46.6316	133.0264
☐ Max contact diameter dja	56.8520	143.2256
☐ Min contact diameter djf	47.5086	135.2138
☐ Input diameter		

☑ common nomal line

☐ Pinion rotation angle correction 0.0000 deg

Pinion rotation angle 0.0000 deg

Fig.45.7 meshing drawing & support form



X axis rotation angle	-60	deg
Y axis rotation angle	65	deg
Z axis rotation angle	30	deg
Scaling	185	%
Speculer power	70	%
Gear opacity	100	%
Rotation interval	10	mmSec
Rotating	0	μdeg
Discrepancy	0	μdeg
Parallel	0	μdeg

Fig.45.8 tooth profile rendering & support form

45.6 Contact line and sliding ratio graph

The contact line graph is shown in Fig.45.8. This graph shows the relation of the meshing well because the line of action length of the gear is shown in the vertical axis with the line of action length of the pinion shown in the transverse. In the Fig.45.9, when the contact diameter of the pinion is 50.030 mm, the contact diameter of the gear is 139.969 mm. Also, the line of action length of this pinion is 9.749.657 mm and the gear is 27.145 mm.

Moreover, the meshing of the tooth can be grasped because are connected with contact profile (Fig.45.7). The rotation angle computation (Fig.45.10) is the auxiliary calculation function to compute relation between the contact diameter, the line of action length and the roll angle and then the rotation angle. And, the sliding ratio graph is shown in Fig.45.11.

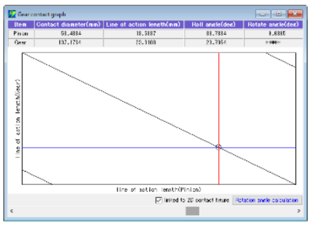
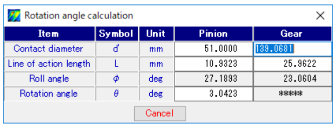


Fig.45.9 contact line



Item	Symbol	Unit	Pinion	Gear
Contact diameter	d'	mm	51.0000	139.0681
Line of action length	L	mm	10.9323	25.9622
Roll angle	φ	deg	27.1893	23.0604
Rotation angle	θ	deg	3.0423	*****

Fig.45.10 rotation angle

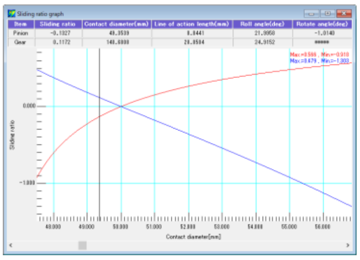
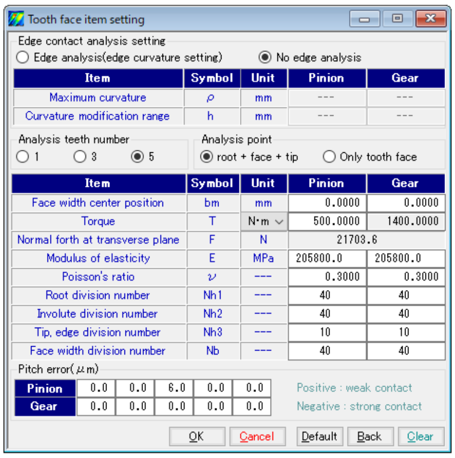


Fig.45.11 sliding ratio

45.7 Tooth surface element setting

The tooth surface element setting is shown in Fig.45.12. It sets a torque, and Young's modulus, Poisson's ratio and then the tooth profile distribution number and a pitch error with this screen. The plastic gear can be analyzed by setting Young's modulus and Poisson's ratio. The analysis tooth profile can choose 1 tooth, 3 teeth, 5 teeth. It chooses 5 teeth when total contact ratio is big and having a pitch error. In the analysis of the example gear, it gives the pinion a 6μm pitch error.


Tooth face item setting

Edge contact analysis setting
○ Edge analysis(edge curvature setting) ● No edge analysis

Item	Symbol	Unit	Pinion	Gear
Maximum curvature	ρ	mm	---	---
Curvature modification range	h	mm	---	---

Analysis teeth number: ○ 1 ○ 3 ● 5
Analysis point: ● root + face + tip ○ Only tooth face

Item	Symbol	Unit	Pinion	Gear
Face width center position	bm	mm	0.0000	0.0000
Torque	T	N·m	500.0000	1400.0000
Normal forth at transverse plane	F	N	21703.6	
Modulus of elasticity	E	MPa	205800.0	205800.0
Poisson's ratio	ν	---	0.3000	0.3000
Root division number	Nh1	---	40	40
Involute division number	Nh2	---	40	40
Tip, edge division number	Nh3	---	10	10
Face width division number	Nb	---	40	40

Pitch error(μm)

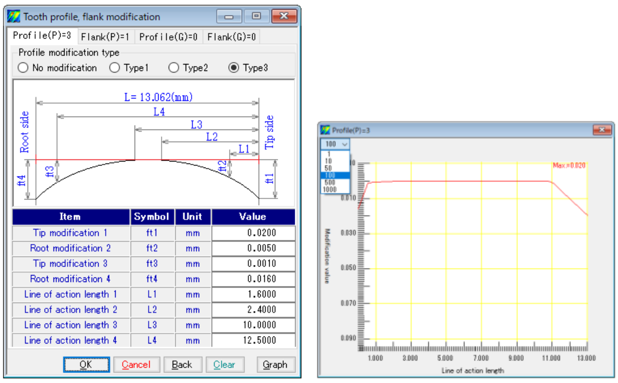
Pinion	0.0	0.0	6.0	0.0	0.0
Gear	0.0	0.0	0.0	0.0	0.0

Positive : weak contact
Negative : strong contact

Fig.45.12 tooth surface element setting

45.8 The profile and lead modification setting

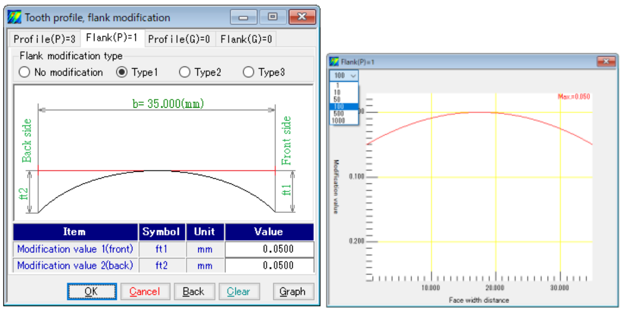
There are a profile and lead modification and three kinds (Type1-3) of the fixed form respectively. In this example, it gives the pinion a profile modification (Fig.45.13, 45.14) but a gear isn't modification.


Tooth profile, flank modification

Profile modification type
○ No modification ○ Type1 ○ Type2 ● Type3

Item	Symbol	Unit	Value
Tip modification 1	ft1	mm	0.0200
Root modification 2	ft2	mm	0.0050
Tip modification 3	ft3	mm	0.0010
Root modification 4	ft4	mm	0.0160
Line of action length 1	L1	mm	1.6000
Line of action length 2	L2	mm	2.4000
Line of action length 3	L3	mm	10.0000
Line of action length 4	L4	mm	12.5000

Fig.45.13 tooth modification and graph (×100)


Tooth profile, flank modification

Flank modification type
○ No modification ● Type1 ○ Type2 ○ Type3

Item	Symbol	Unit	Value
Modification value 1(front)	ft1	mm	0.0500
Modification value 2(back)	ft2	mm	0.0500

Fig45.14 lead modification and graph (×100)

45.9 Tooth modification (3D) setting

Like Fig.45.15, the tooth surface modification (3D) can type in directly. Also, the profile modification which was set at Fig.45.13 and Fig.45.14 can be taken over, too. As for Fig.45.15, it is displaying the modification which was set at Fig.45.13 and Fig.45.14 by 3D-profile (gear is a theory tooth profile.). This tooth profile can be output by the [CSV] file. Also, this screen can read the inspection data.

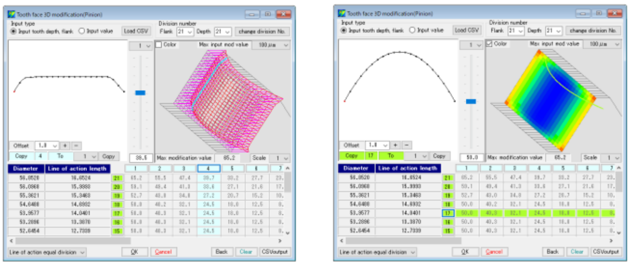

(a) Setting &profile modification (b) color palette distribution

Fig.45.15 profile modification (Ex. pinion)

45.10 Profile modification & tooth surface stress (3D)

The tooth profile which was set with the Fig.45.15 can be confirmed with 3D figure. The gear can be turned by the support form and it is possible to make it magnify a gear figure. Moreover, the contact pattern by the tooth when giving an error can be confirmed. Fig.45.16(a) is a modified tooth profile and (b) is the adjusted figure which piled a theory tooth profile on it. Also, a tooth surface element mesh model is shown to Fig.45.17.

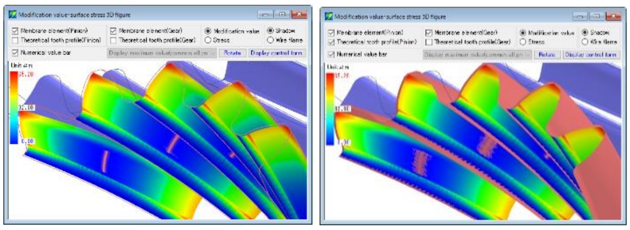

(a) tooth modification (b) tooth modification + profile

Fig.45.16 tooth surface element

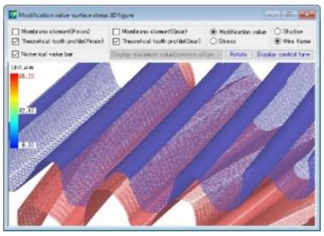
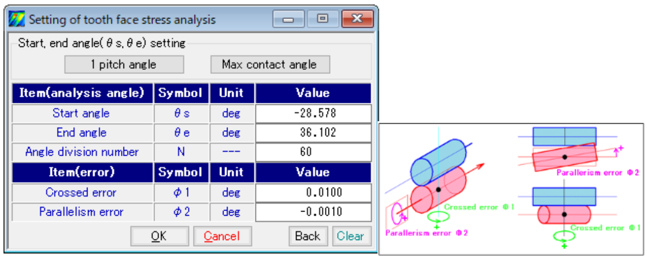


Fig.45.17 tooth surface element model（mesh / Fig45.12）

45.11 Tooth surface stress analysis condition setting

The gear specification and torque and then, it analyzes the tooth surface stress when giving a tooth surface modification. There are two 1 angle pitch and maximum contact angle kinds of setting of an analysis angle range (Free angle can be set). It sets start angle θ_S=-28.578° and end angle θ_e=36.102° like Fig.45.18 as the computation and divide that contact angle into 60. Then calculate by giving discrepancy error φ_1=0.01° and parallelism error φ_2=-0.001°. This axis angle error is the error angle when the bearing or the gear box is distorted by the load, which causes a change in the tooth contact and a change in the stress distribution.


Setting of tooth face stress analysis

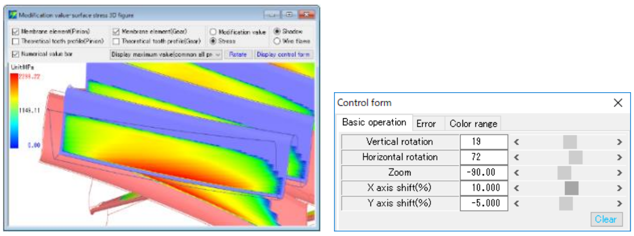
Start, end angle(θs, θe) setting

Item(analysis angle)	Symbol	Unit	Value
Start angle	θs	deg	-28.578
End angle	θe	deg	36.102
Angle division number	N	---	60
Item(error)	**Symbol**	**Unit**	**Value**
Crossed error	φ1	deg	0.0100
Parallelism error	φ2	deg	-0.0010

Fig.45.18 tooth surface analysis setting screen, ϕ_1 and ϕ_2

45.12 Tooth surface stress analysis result (3D diagram)

Since the pitch error is given in Fig.45.12, the tooth stress analysis result changes stress distribution depending on the tooth as shown in Fig. 45.19. However, Fig.45.20 shows the maximum stress on all teeth, so all teeth have the same stress distribution. Fig.45.21 shows the maximum and minimum of the tooth surface stress, and it can be seen that the maximum tooth surface stress is when the pinion rotation angle θ_p= 14.177 °.



Control form

Basic operation | Error | Color range

Vertical rotation 19

Horizontal rotation 72

Zoom -90.00

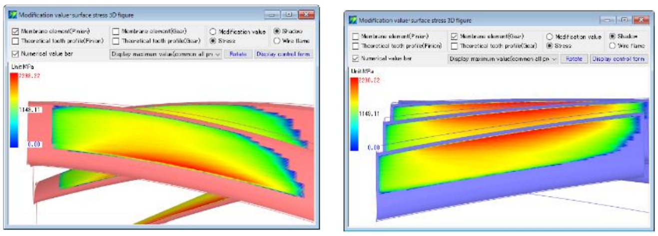
X axis shift(%) 10.000

Y axis shift(%) -5.000

Clear

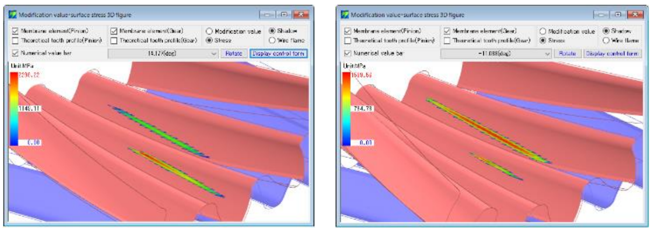
analysis result which contains a pitch-error and support form

Fig.45.19 tooth surface stress （σ_{Hmax}=2298MPa）



(a) pinion (b) gear

Fig.45.20 tooth surface stress （σ_{Hmax}=2298MPa）



(a)σ_{Hmax}=2298MPa(θ_p=14.177°) (b) σ_{Hmin}=1590MPa(θ_p=-11.04°)

Fig.45.21 maximum and minimum value of the tooth surface stress

Fig.45.22 shows the stress distribution (cell display) of the entire tooth surface. In the case of a pinion, stress in the area of 98 in the tooth width direction (including the tooth width chamfer) and 90 in the tooth direction (including the tooth tip chamfer) is displayed, so the stress value at the tooth surface position is understood. In addition, the stress value displayed here can be output as a CSV file. As for the stress at each rotation angle, as shown in Fig. 45.23, stress distribution corresponding to pinion rotation angle can be displayed continuously, so you can grasp stress change and contact position.

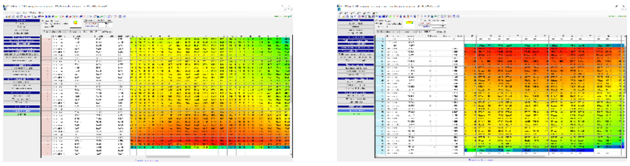


Fig.45.22 tooth surface stress （σ_{Hmax}=2298MPa）

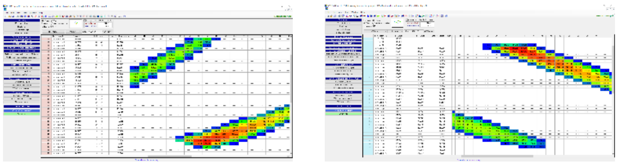
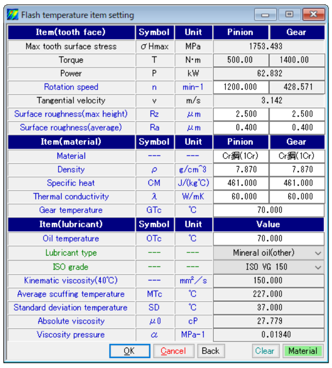


Fig.45.23 θ_p=14.177° （σ_{Hmax}=2298MPa）

45.13 Flash temperature, friction coefficient, oil film thickness etc.

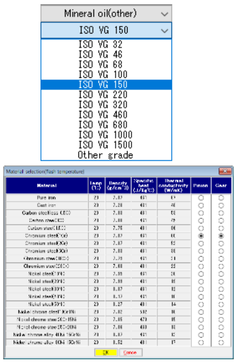
Fig.45.24 shows the setting screen for flash temperature calculation. Here, material (thermal conductivity) is selected in addition to the rotation speed and tooth surface roughness (Fig. 45.25). Mineral oils and synthetic oils can be selected for the type of lubricant, but in case of nonstandard, kinematic viscosity and average temperature of oil can be arbitrarily set. Calculation results of flash temperature, coefficient of friction, oil film thickness are shown in Fig.45.26 to 45.33. The probability of occurrence of scuffing and probability of wear are shown in Fig.45.34.



Flash temperature item setting

Item(tooth face)	Symbol	Unit	Pinion	Gear
Max tooth surface stress	σHmax	MPa	1753.493	
Torque	T	N·m	500.00	1400.00
Power	P	kW	62.832	
Rotation speed	n	min-1	1200.000	428.571
Tangential velocity	v	m/s	3.142	
Surface roughness(max height)	Rz	μm	2.500	2.500
Surface roughness(average)	Ra	μm	0.400	0.400
Item(material)	**Symbol**	**Unit**	**Pinion**	**Gear**
Material	---	---	Cr鋼(1Cr)	Cr鋼(1Cr)
Density	ρ	g/cm^3	7.870	7.870
Specific heat	CM	J/(kg℃)	461.000	461.000
Thermal conductivity	λ	W/mK	60.000	60.000
Gear temperature	GTc	℃	70.000	
Item(lubricant)	**Symbol**	**Unit**	**Value**	
Oil temperature	OTc	℃	70.000	
Lubricant type	---	---	Mineral oil(other)	
ISO grade	---	---	ISO VG 150	
Kinematic viscosity(40℃)	---	mm²/s	150.000	
Average scuffing temperature	MTc	℃	227.000	
Standard deviation temperature	SD	℃	37.000	
Absolute viscosity	μ0	cP	27.779	
Viscosity pressure	α	MPa-1	0.01940	

Fig.45.24 flash temperature setting

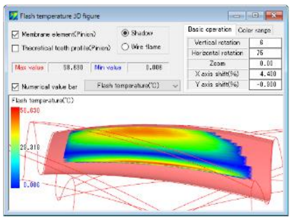


Mineral oil(other)

ISO VG 150

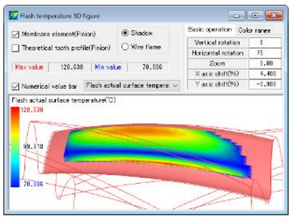
- ISO VG 32
- ISO VG 46
- ISO VG 68
- ISO VG 100
- ISO VG 150
- ISO VG 220
- ISO VG 320
- ISO VG 460
- ISO VG 680
- ISO VG 1000
- ISO VG 1500
- Other grade

Fig.45.25 material and oil



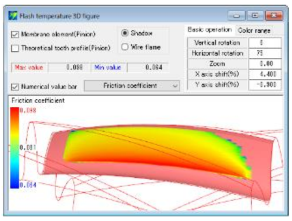
T_{fl}=58.6(℃)

Fig.45.26 flash temperature



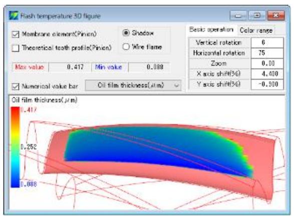
T_{flB}=128.6(℃)

Fig.45.27 gear temperature



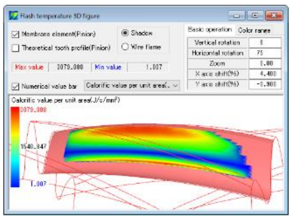
μ_{max}=0.098

Fig.45.28 friction coefficient



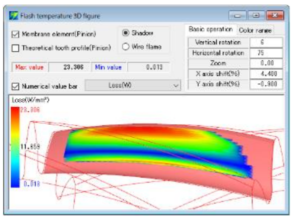
λ_{min}=0.088(μm)

Fig.45.29 oil film thickness



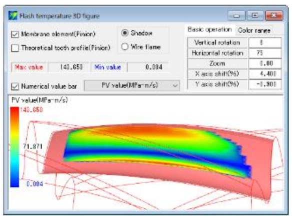
J_{max}=3080(J/s/mm^2)

Fig.45.30 calorific value



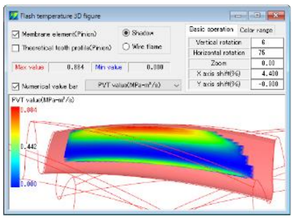
W_{max}=23.3(W/mm^2)

Fig.45.31 power loss



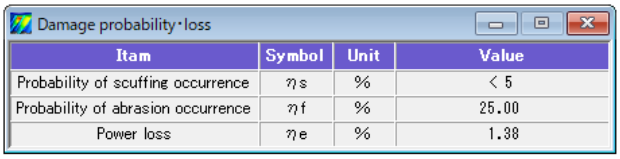
PV_{max}=144(MPa-m/s)

Fig.45.32 PV value



PVT_{max}=0.884(MPa-m^2/s)

Fig.45.33 PVT value



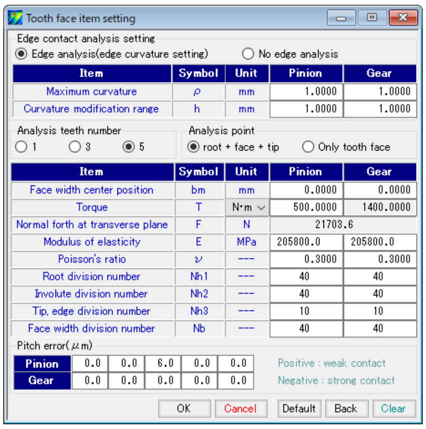
Damage probability･loss

Item	Symbol	Unit	Value
Probability of scuffing occurrence	ηs	%	< 5
Probability of abrasion occurrence	ηf	%	25.00
Power loss	ηe	%	1.38

Fig.45.34 damage probability

45.14 Edge analysis (option)

In paragraphs 45.11 to 45.14, we analyzed the involute tooth surface, but here we show the result of the end analysis of the tooth tip and side part (Fig.45.35, end set at R = 1.0 mm). As a result of analysis, as shown in Fig.45.36, large stress σ_{Hmax}=4075 MPa is generated in pinion tooth and gear tooth tip. In the analysis of the involute tooth surface, the flash temperature is 58.5 ° C at the tooth tip as shown in Fig.45.26. However, in the edge analysis, it can be seen that as shown in Fig.45.37, the pinion tooth rose greatly to 182 ° C.



Tooth face item setting

Edge contact analysis setting

● Edge analysis(edge curvature setting) ○ No edge analysis

Item	Symbol	Unit	Pinion	Gear
Maximum curvature	ρ	mm	1.0000	1.0000
Curvature modification range	h	mm	1.0000	1.0000

Analysis teeth number: ○ 1 ○ 3 ● 5

Analysis point: ● root + face + tip ○ Only tooth face

Item	Symbol	Unit	Pinion	Gear
Face width center position	bm	mm	0.0000	0.0000
Torque	T	N･m	500.0000	1400.0000
Normal forth at transverse plane	F	N	21703.6	
Modulus of elasticity	E	MPa	205800.0	205800.0
Poisson's ratio	ν	---	0.3000	0.3000
Root division number	Nh1	---	40	40
Involute division number	Nh2	---	40	40
Tip, edge division number	Nh3	---	10	10
Face width division number	Nb	---	40	40

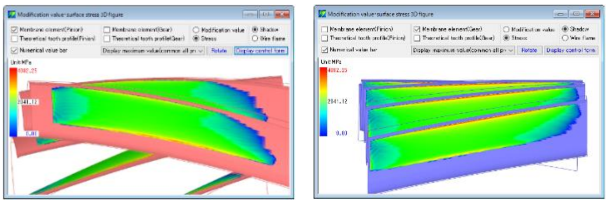
Pitch error(μm)

Pinion	0.0	0.0	6.0	0.0	0.0
Gear	0.0	0.0	0.0	0.0	0.0

Positive : weak contact

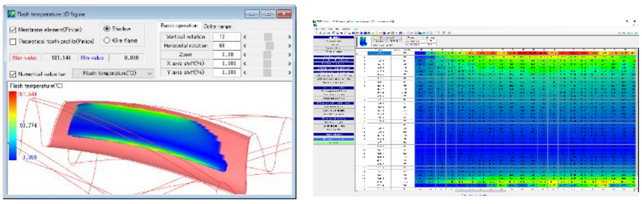
Negative : strong contact

Fig.45.35 tooth surface element setting (edge analysis)



(a) pinion (b) gear

Fig.45.36 tooth surface stress (edge analysis, σ_{Hmax}=4082MPa)

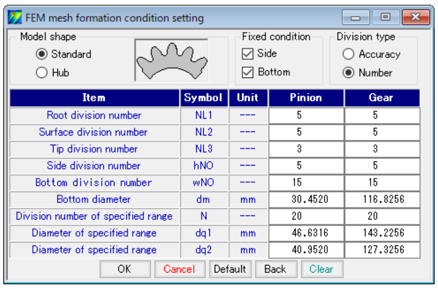


(a) tooth profile (b) cell

Fig.45.37 flash temperature, T_{fl}=182(℃)

45.15 FEM analysis

In the analysis condition of Fig.45.12, to make FEM analysis, create a mesh model in Fig.45.38. Here we create a mesh with the standard model, but there are two ways of setting, one is to determine the tooth profile with accuracy and the other is to determine the tooth profile by the number of divisions. The meshed tooth profile can be confirmed with the 2D mesh model as shown in Fig. 45.39. Also, 3D-FEM mesh elements can display the number of elements and the number of nodes as shown in Fig.45.40 and the node coordinates as shown in Fig.45.41.



FEM mesh formation condition setting

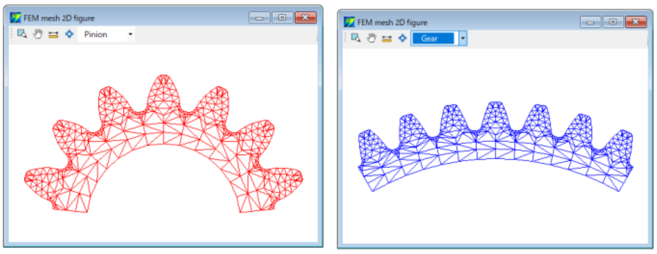
Model shape: ● Standard ○ Hub

Fixed condition: ☑ Side ☑ Bottom

Division type: ○ Accuracy ● Number

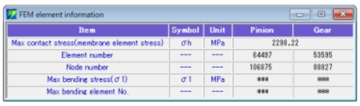
Item	Symbol	Unit	Pinion	Gear
Root division number	NL1	---	5	5
Surface division number	NL2	---	5	5
Tip division number	NL3	---	3	3
Side division number	hNO	---	5	5
Bottom division number	wNO	---	15	15
Bottom diameter	dm	mm	30.4520	116.8256
Division number of specified range	N	---	20	20
Diameter of specified range	dq1	mm	46.6316	143.2256
Diameter of specified range	dq2	mm	40.9520	127.3256

Fig.45.38 mesh model setting



(a) pinion (b) gear

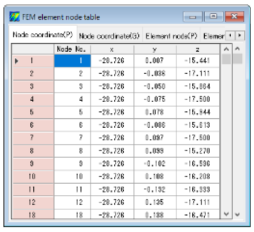
Fig.45.39 2D- mesh model



FEM element information

Item	Symbol	Unit	Pinion	Gear
Max contact stress(membrane element stress)	σh	MPa	2298.22	
Element number	---	---	64497	53595
Node number	---	---	106875	88827
Max bending stress(σ1)	σ1	MPa	***	***
Max bending element No.	---	---	***	***

Fig.45.40 FEM element

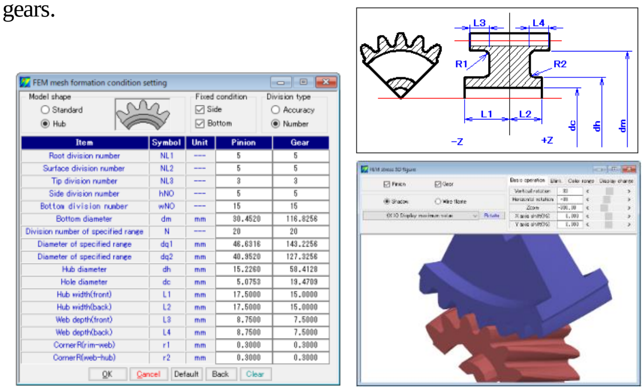


FEM element node table

	Node No.	x	y	z
1	1	-28.726	0.007	-15.441
2	2	-28.726	-0.036	-17.111
3	3	-28.726	-0.050	-15.864
4	4	-28.726	-0.075	-17.500
5	5	-28.726	0.078	-15.944
6	6	-28.726	-0.086	-15.613
7	7	-28.726	0.097	-17.500
8	8	-28.726	0.099	-15.270
9	9	-28.726	-0.102	-16.596
10	10	-28.726	0.108	-16.208
11	11	-28.726	-0.132	-16.333
12	12	-28.726	0.135	-17.111
13	13	-28.726	0.138	-16.471

Fig.45.41 element nod table

The mesh model can be generated as a rim / hub model as shown in Fig.45.42, so it is effective for gears with low elastic modulus like plastic gears.



FEM mesh formation condition setting

Model shape: ○ Standard ● Hub

Fixed condition: ☑ Side ☑ Bottom

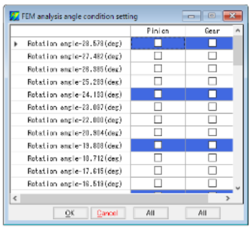
Division type: ○ Accuracy ● Number

Item	Symbol	Unit	Pinion	Gear
Root division number	NL1	---	5	5
Surface division number	NL2	---	5	5
Tip division number	NL3	---	3	3
Side division number	hNO	---	5	5
Bottom division number	wNO	---	15	15
Bottom diameter	dm	mm	30.4520	116.8256
Division number of specified range	N	---	20	20
Diameter of specified range	dq1	mm	46.6316	143.2256
Diameter of specified range	dq2	mm	40.9520	127.3256
Hub diameter	dh	mm	15.2260	58.4128
Hole diameter	dc	mm	5.0753	19.4709
Hub width(front)	L1	mm	17.5000	15.0000
Hub width(back)	L2	mm	17.5000	15.0000
Web depth(front)	L3	mm	8.7500	7.5000
Web depth(back)	L4	mm	8.7500	7.5000
CornerR(rim-web)	r1	mm	0.3000	0.3000
CornerR(web-hub)	r2	mm	0.3000	0.3000

Fig.45.42 rim / hub model

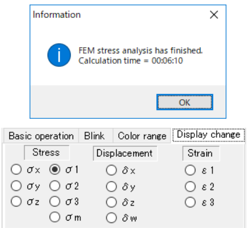
Next, an example of FEM analysis using the mesh model set in Fig. 45.38 is explained below. Set the angle (-28.578 ° to 36.102 °) set in the tooth surface analysis setting in Fig. 45.18 as shown in Fig. 45.43 (angle skipping selection) FEM analysis. The check of □ also includes the angle of θ P = 14.177 ° (Fig.45.21) with the largest tooth surface stress. Also, analyzing all 60 divisions will consume memory and time, so it is effective to select only the required meshing angle and calculate.

The items analyzed by FEM are the stress, displacement and strain shown in Fig.45.44. FEM analysis results are shown in Fig.45.45 to 45.49. The displacement chart can be displayed at 100 times (magnification selection: 1, 5, 10, 50, 100, 200, 500 times) as shown in Fig.45.48.


FEM analysis angle condition setting

	Pinion	Gear
Rotation angle-28.578(deg)	☐	☐
Rotation angle-27.482(deg)	☐	☐
Rotation angle-26.385(deg)	☐	☐
Rotation angle-25.289(deg)	☐	☐
Rotation angle-24.193(deg)	☐	☐
Rotation angle-23.097(deg)	☐	☐
Rotation angle-22.000(deg)	☐	☐
Rotation angle-20.904(deg)	☐	☐
Rotation angle-19.808(deg)	☐	☐
Rotation angle-18.712(deg)	☐	☐
Rotation angle-17.615(deg)	☐	☐
Rotation angle-16.519(deg)	☐	☐

Fig.45.43　FEM analysis choice


Information

FEM stress analysis has finished.
Calculation time = 00:06:10

Stress: ○ σx ● $\sigma 1$ ○ σy ○ $\sigma 2$ ○ σz ○ $\sigma 3$ ○ σm
Displacement: ○ δx ○ δy ○ δz ○ δw
Strain: ○ $\varepsilon 1$ ○ $\varepsilon 2$ ○ $\varepsilon 3$

Fig.45.44　kind of the analysis

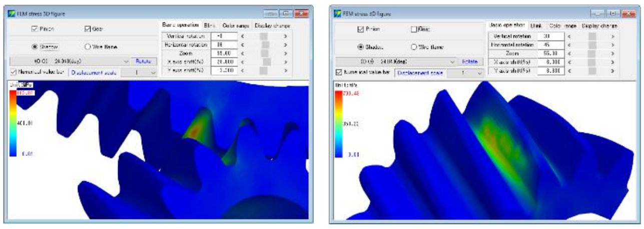

(a) one pair gear　(b) pinion, σ_{mmax}=837MPa

Fig.45.45　σ_m (Mises stress), θ_p=24.043°

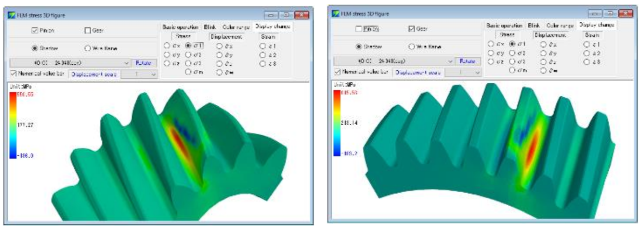

(a) pinion,　σ_{1max}=551MPa　(b) gear, σ_{1max}=616MPa

Fig.45.46　maximum principal stress, θ_p=24.043°

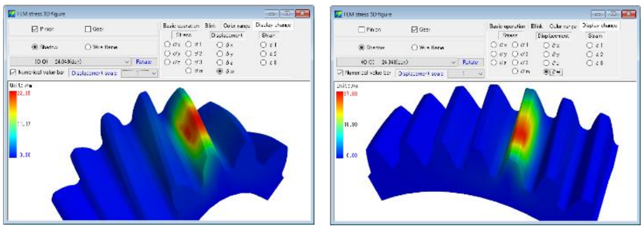

(a) pinion,　δ_{max}=22.4μm　(b) gear, δ_{max}=37.8μm

Fig.45.47　displacement, θ_p=24.043°

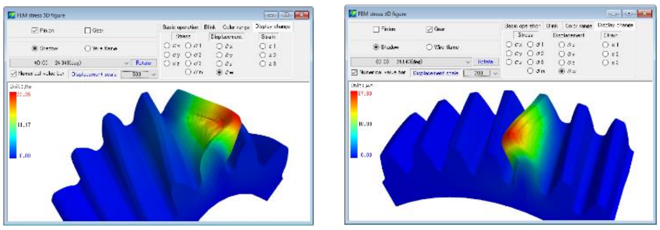

(a) pinion,　×500　(b) gear,　×200

Fig.45.48　displacement (zoom), θ_p=24.043°

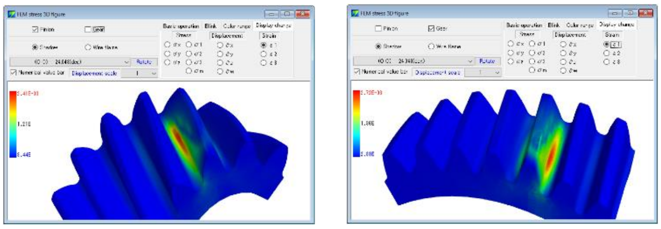

(a) pinion, ε_{1max}=2.41×10^{-3}　(b) gear, ε_{1max}=2.72×10^{-3}

Fig.45.49　distortion, θ_p=24.043°

In Fig.45.43, we analyze the pinion rotation angle as θp = -28.578 to 36.102((Fig.45.18). When we summarize this, we can see that since the pitch error (Fig. 45.12, 6 μm) is given as shown in Fig.45.50, the dedendum stress greatly changes. In Fig. 45.50, the angle showing the maximum value is θ_p = 19.665 °, and its maximum stress is σ1max (P) = 551MPa and σ1max (G) = 617MPa. An analysis list at this angle is shown in Fig.45.51.

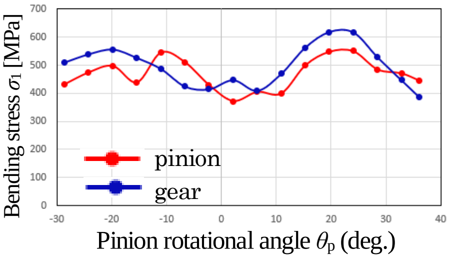


Fig.45.50　change of the filet stress (σ_{1max})

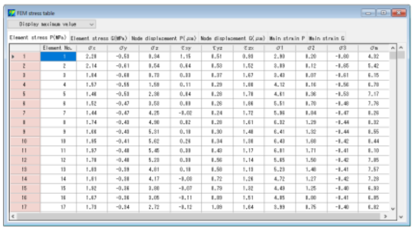


Fig.45.51　analysis result list

It is understood that the element number of the maximum value σ 1 max=551 MPa of the maximum principal stress of the pinion in the analysis result list is 37766. If you enter this number in "blinking" in Fig.45.52, you can check with the stress distribution map (▲flashes in ○). After completion of FEM analysis, stress at any position in the tooth width direction can be displayed as shown in Fig. 45.53. Fig.45.53 shows the stress distribution at the tooth width center section position (zd = 0 mm). For reference, Fig.45.54 shows the tooth root stress distribution in the analysis angle range.

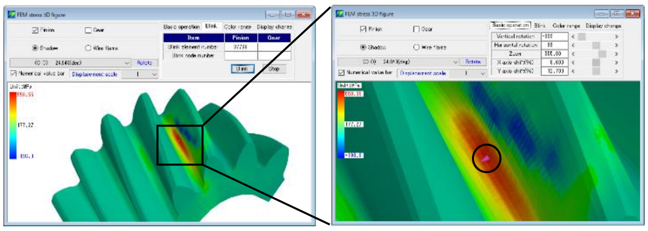


Fig.45.52　pinion, σ_{1max} point, σ_{1max}=555MPa

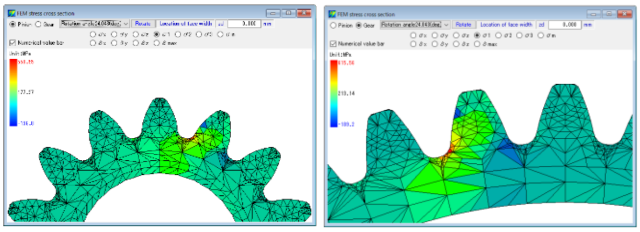

(a) pinion, σ_{1max}=551MPa　(b) gear, σ_{1max}=616MPa

Fig.45.53　FEM-section (zd=0mm)

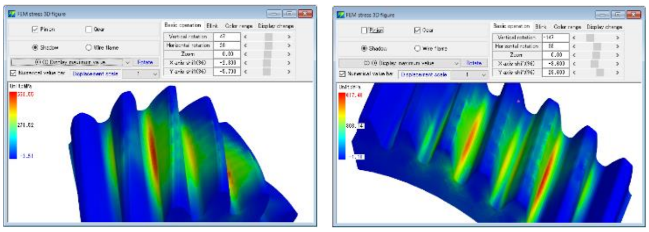
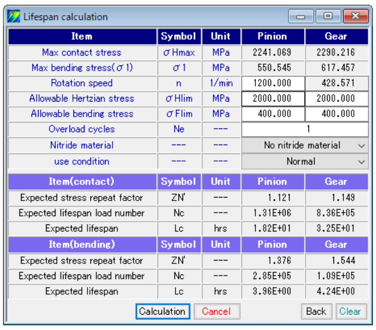

(a)ピニオン　σ_{1max}=551MPa　(b)　ギヤ　σ_{1max}=616MPa

Fig.45.54　fillet stress in the analysis angle range

45.16 Lifetime

Calculate lifetime after tooth surface stress analysis and FEM analysis. Fig.45.55 shows the lifetime when the allowable stress value for material's tooth surface strength is σ_{Hlim}=2000 MPa and the allowable stress value for bending strength is σ_{Flim}=400 MPa.


Lifespan calculation

Item	Symbol	Unit	Pinion	Gear
Max contact stress	σHmax	MPa	2241.069	2298.216
Max bending stress(σ1)	σ1	MPa	550.545	617.457
Rotation speed	n	1/min	1200.000	428.571
Allowable Hertzian stress	σHlim	MPa	2000.000	2000.000
Allowable bending stress	σFlim	MPa	400.000	400.000
Overload cycles	Ne	---	1	
Nitride material	---	---	No nitride material	
use condition	---	---	Normal	
Item(contact)	**Symbol**	**Unit**	**Pinion**	**Gear**
Expected stress repeat factor	ZN'	---	1.121	1.149
Expected lifespan load number	Nc	---	1.31E+06	8.36E+05
Expected lifespan	Lc	hrs	1.82E+01	3.25E+01
Item(bending)	**Symbol**	**Unit**	**Pinion**	**Gear**
Expected stress repeat factor	ZN'	---	1.376	1.544
Expected lifespan load number	Nc	---	2.85E+05	1.09E+05
Expected lifespan	Lc	hrs	3.96E+00	4.24E+00

Fig.45.55　lifetime

45.17　Transmission error (option)

Fig.45.56 shows the rotation transmission error within the rotation angle given in the tooth surface analysis setting screen, and Fig.45.57 shows the Fourier analysis result.

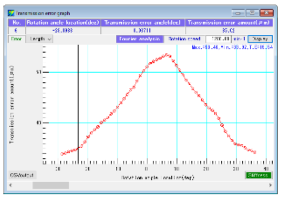


Fig.45.56　transmission error

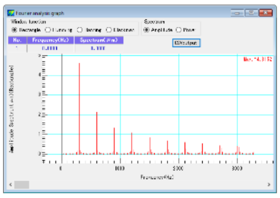


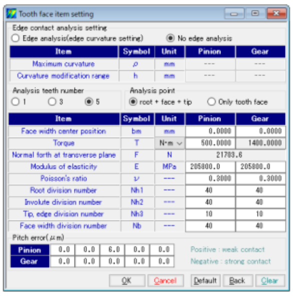
Fig.45.57　Fourier analyses

45.18　Analysis of optimal tooth surface modification

As shown in Fig. 45.14, instead of uniformly determining the tooth surface modification, it is a function that can determine the amount of correction that minimizes tooth surface stress when considering torque, pitch error, and shaft angle error. It is possible to reduce the tooth surface stress generated by applying appropriate tooth surface modification.

As an example, Fig. 45.4 When the torque of Fig. 45.58 is applied with the gear and the discrepancy error of the shaft is set to φ1 = 0.01 ° and the parallelism error is set to φ2 = -0.001 ° as shown in Fig. 45.59, when the modification distribution ratio is set to 0.5, You can obtain tooth surface modification like 45.60 (finely adjusted tooth surface shape generated by optimal tooth surface modification). Fig.45.61 to 45.65 calculate the tooth surface stress, flash temperature, friction coefficient, etc. based on this tooth surface modification, the tooth root stress is shown in Fig.45.67, and the life time is shown in Fig.45.68.

As a result, since the tooth surface stress decreases from σ_{Hmax}=2295 MPa (Fig. 45.20) to σ_{Hmax}=1637 MPa, the life time to the tooth surface has also been dramatically extended.


Tooth face item setting

Edge contact analysis setting
○ Edge analysis(edge curvature setting)　● No edge analysis

Item	Symbol	Unit	Pinion	Gear
Maximum curvature	ρ	mm	---	---
Curvature modification range	h	mm	---	---

Analysis teeth number: ○ 1　○ 3　● 5
Analysis point: ● root + face + tip　○ Only tooth face

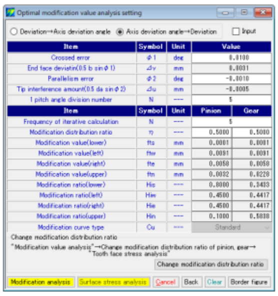
Item	Symbol	Unit	Pinion	Gear
Face width center position	bm	mm	0.0000	0.0000
Torque	T	N･m	500.0000	1400.0000
Normal forth at transverse plane	F	N	21703.6	
Modulus of elasticity	E	MPa	205800.0	205800.0
Poisson's ratio	ν	---	0.3000	0.3000
Root division number	Nh1	---	40	40
Involute division number	Nh2	---	40	40
Tip, edge division number	Nh3	---	10	10
Face width division number	Nb	---	40	40

Pitch error(μm)

Pinion	0.0	0.0	6.0	0.0	0.0
Gear	0.0	0.0	0.0	0.0	0.0

Positive : weak contact
Negative : strong contact

Fig.45.58　torque setting


Optimal modification value analysis setting

○ Deviation→Axis deviation angle　● Axis deviation angle→Deviation　☐ Input

Item	Symbol	Unit	Value
Crossed error	φ1	deg	0.0100
End face deviatin(0.5 b sin φ 1)	Δv	mm	0.0031
Parallelism error	φ2	deg	-0.0010
Tip interference amount(0.5 da sin φ 2)	Δu	mm	-0.0005
1 pitch angle division number	N	---	5

Item	Symbol	Unit	Pinion	Gear
Frequency of iterative calculation	N	---	5	
Modification distribution ratio	η	---	0.5000	0.5000
Modification value(lower)	fts	mm	0.0001	0.0001
Modification value(left)	ftw	mm	0.0091	0.0091
Modification value(right)	fte	mm	0.0058	0.0058
Modification value(upper)	ftn	mm	0.0032	0.0228
Modification ratio(lower)	His	---	0.8000	0.3433
Modification ratio(left)	Hiw	---	0.4500	0.4417
Modification ratio(right)	Hie	---	0.4500	0.4417
Modification ratio(upper)	Hin	---	0.1000	0.5838
Modification curve type	Cu	---	Standard	

Change modification distribution ratio
"Modification value analysis"→Change modification distribution ratio of pinion, gear→"Tooth face stress analysis"

Fig.45.59　modification setting

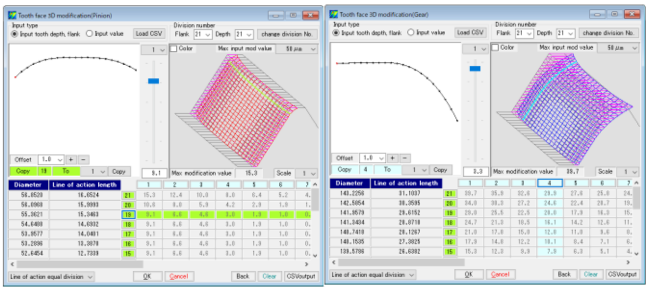

(a) pinion　　(b) gear

Fig.45.60　optimal tooth surface modification

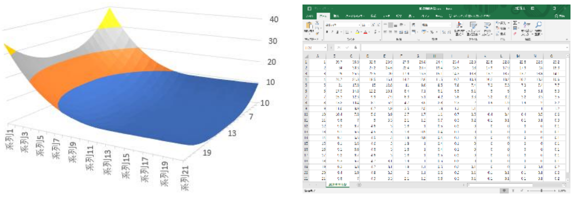

[csv] output, Fig.45.60(b)

Fig.45.61　optimal tooth surface modification (Excel)

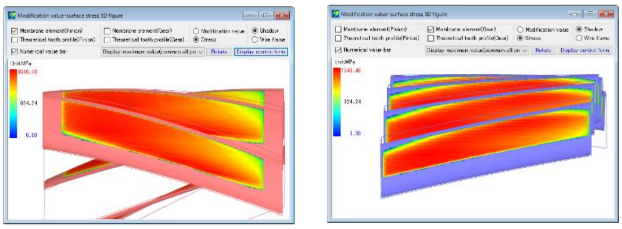

(a) pinion　　(b) gear

Fig.45.62　tooth surface stress (σ_{Hmax}=1648MPa)

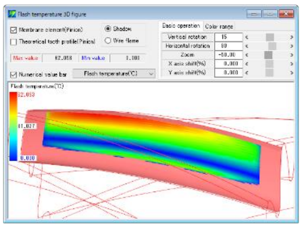

T_{fl}=62.1(℃)

Fig.45.63　flash temperature

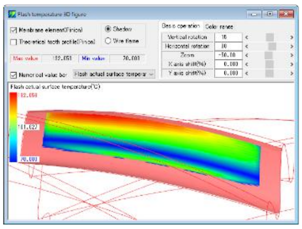

T_{flB}=132(℃)

Fig.45.64　gear temperature

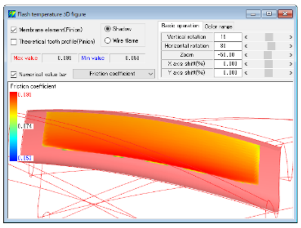

μ_{max}=0.095

Fig.45.65　friction coefficient

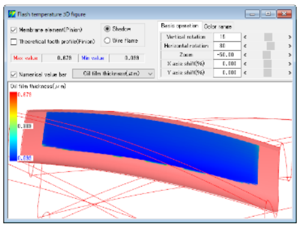

λ_{min}=0.099(μm)

Fig.45.66　oil film thickness

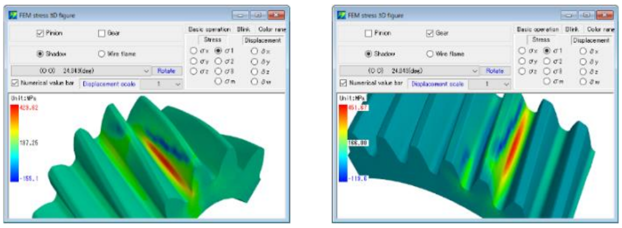
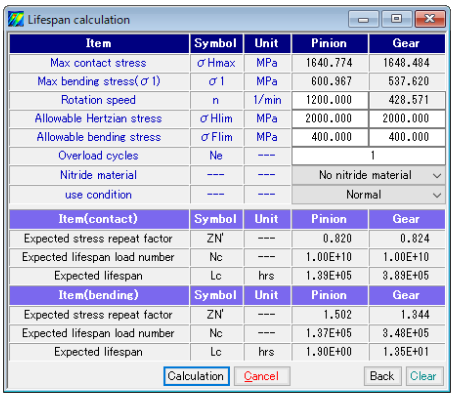

(a) pinion, $\sigma_{1\mathrm{max}}$=430MPa　　(b) gear,　$\sigma_{1\mathrm{max}}$=452MPa

Fig.45.67　maximum principal stress, θ_p=24.043°

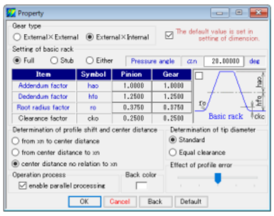

Lifespan calculation

Item	Symbol	Unit	Pinion	Gear
Max contact stress	σHmax	MPa	1640.774	1648.484
Max bending stress(σ1)	σ1	MPa	600.967	537.620
Rotation speed	n	1/min	1200.000	428.571
Allowable Hertzian stress	σHlim	MPa	2000.000	2000.000
Allowable bending stress	σFlim	MPa	400.000	400.000
Overload cycles	Ne	---	1	
Nitride material	---	---	No nitride material	
use condition	---	---	Normal	
Item(contact)	**Symbol**	**Unit**	**Pinion**	**Gear**
Expected stress repeat factor	ZN'	---	0.820	0.824
Expected lifespan load number	Nc	---	1.00E+10	1.00E+10
Expected lifespan	Lc	hrs	1.39E+05	3.89E+05
Item(bending)	**Symbol**	**Unit**	**Pinion**	**Gear**
Expected stress repeat factor	ZN'	---	1.502	1.344
Expected lifespan load number	Nc	---	1.37E+05	3.48E+05
Expected lifespan	Lc	hrs	1.90E+00	1.35E+01

Fig.45.68 lifetime

45.19 Analysis of the internal-gear（option）

The analysis result of "external gear × internal gear" is shown Fig.45.69 to 45.84.


Property

Gear type: ○ External×External ● External×Internal

☑ The default value is set in setting of dimension.

Setting of basic rack: ● Full ○ Stub ○ Either

Pressure angle αn 20.00000 deg

Item	Symbol	Pinion	Gear
Addendum factor	hao	1.0000	1.0000
Dedendum factor	hfo	1.2500	1.2500
Root radius factor	ro	0.3750	0.3750
Clearance factor	cko	0.2500	0.2500

Determination of profile shift and center distance: ○ from xn to center distance ○ from center distance to xn ● center distance no relation to xn

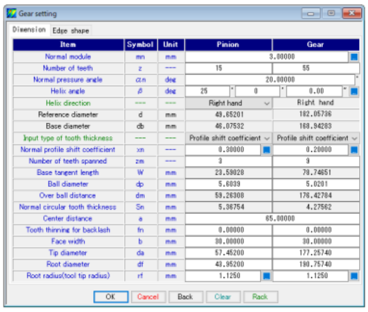
Determination of tip diameter: ● Standard ○ Equal clearance

Effect of profile error

Operation process: ☑ enable parallel processing

Back color

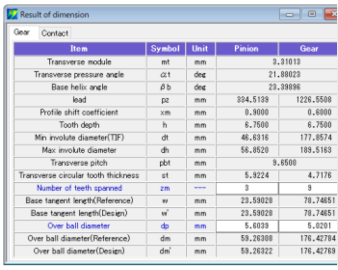
Fig.45.69 basic rack


Gear setting

Dimension | Edge shape

Item	Symbol	Unit	Pinion	Gear
Normal module	mn	mm	3.00000	
Number of teeth	z	---	15	55
Normal pressure angle	αn	deg	20.00000	
Helix angle	β	deg	25 ° 0 ' 0.00 "	
Helix direction	---	---	Right hand	Right hand
Reference diameter	d	mm	49.65201	182.05736
Base diameter	db	mm	46.07532	168.94283
Input type of tooth thickness	---	---	Profile shift coefficient	Profile shift coefficient
Normal profile shift coefficient	xn	---	0.30000	0.20000
Number of teeth spanned	zm	---	3	9
Base tangent length	W	mm	23.59028	78.74651
Ball diameter	dp	mm	5.6039	5.0201
Over ball distance	dm	mm	59.26308	176.42784
Normal circular tooth thickness	Sn	mm	5.36754	4.27562
Center distance	a	mm	65.00000	
Tooth thinning for backlash	fn	mm	0.00000	0.00000
Face width	b	mm	30.00000	30.00000
Tip diameter	da	mm	57.45200	177.25740
Root diameter	df	mm	43.95200	190.75740
Root radius(tool tip radius)	rf	mm	1.1250	1.1250

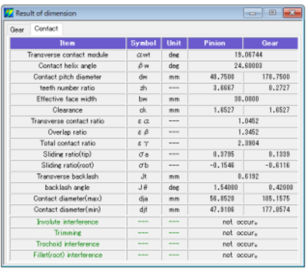
Fig.45.70 gear specification


Result of dimension

Gear | Contact

Item	Symbol	Unit	Pinion	Gear
Transverse module	mt	mm	3.31013	
Transverse pressure angle	αt	deg	21.88023	
Base helix angle	βb	deg	23.39896	
lead	pz	mm	334.5139	1226.5508
Profile shift coefficient	xm	mm	0.9000	0.6000
Tooth depth	h	mm	6.7500	6.7500
Min involute diameter(TIF)	dt	mm	46.6316	177.8574
Max involute diameter	dh	mm	56.8520	189.5163
Transverse pitch	pbt	mm	9.6500	
Transverse circular tooth thickness	st	mm	5.9224	4.7176
Number of teeth spanned	zm	---	3	9
Base tangent length(Reference)	w	mm	23.59028	78.74651
Base tangent length(Design)	w'	mm	23.59028	78.74651
Over ball diameter	dp	mm	5.6039	5.0201
Over ball diameter(Reference)	dm	mm	59.26308	176.42784
Over ball diameter(Design)	dm'	mm	59.26322	176.42769

Fig.45.71 dimension result-1


Result of dimension

Gear | Contact

Item	Symbol	Unit	Pinion	Gear
Transverse contact module	αwt	deg	19.06744	
Contact helix angle	βw	deg	24.60003	
Contact pitch diameter	dw	mm	48.7500	178.7500
teeth number ratio	zh	---	3.6667	0.2727
Effective face width	bw	mm	30.0000	
Clearance	ck	mm	1.6527	1.6527
Transverse contact ratio	εα	---	1.0452	
Overlap ratio	εβ	---	1.3452	
Total contact ratio	εγ	---	2.3904	
Sliding ratio(tip)	σa	---	0.3795	0.1339
Sliding ratio(root)	σb	---	-0.1546	-0.6116
Transverse backlash	Jt	mm	0.6192	
backlash angle	Jθ	deg	1.54000	0.42000
Contact diameter(max)	dja	mm	56.8520	185.1575
Contact diameter(min)	djf	mm	47.9106	177.8574
Involute interference	---	---	not occur。	
Trimming	---	---	not occur。	
Trochoid interference	---	---	not occur。	
Fillet(root) interference	---	---	not occur。	

Fig.45.72 dimension result-2

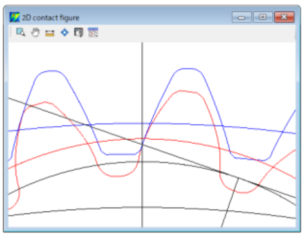


Fig.45.73 meshing drawing

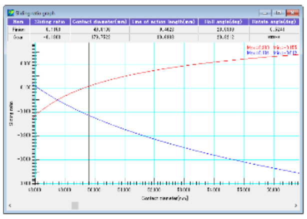
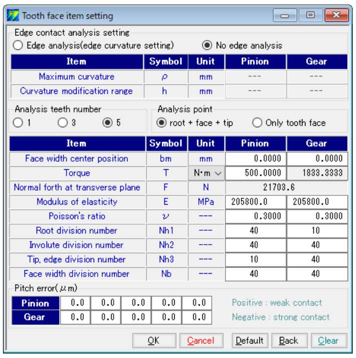


Fig.45.74 sliding ratio


Tooth face item setting

Edge contact analysis setting: ○ Edge analysis(edge curvature setting) ● No edge analysis

Item	Symbol	Unit	Pinion	Gear
Maximum curvature	ρ	mm	---	---
Curvature modification range	h	mm	---	---

Analysis teeth number: ○ 1 ○ 3 ● 5

Analysis point: ● root + face + tip ○ Only tooth face

Item	Symbol	Unit	Pinion	Gear
Face width center position	bm	mm	0.0000	0.0000
Torque	T	N·m	500.0000	1833.3333
Normal forth at transverse plane	F	N	21703.6	
Modulus of elasticity	E	MPa	205800.0	205800.0
Poisson's ratio	ν	---	0.3000	0.3000
Root division number	Nh1	---	40	10
Involute division number	Nh2	---	40	40
Tip, edge division number	Nh3	---	10	40
Face width division number	Nb	---	40	40

Pitch error(μm)

Pinion	0.0	0.0	0.0	0.0	0.0
Gear	0.0	0.0	0.0	0.0	0.0

Positive : weak contact
Negative : strong contact

Fig.45.75 tooth surface element setting

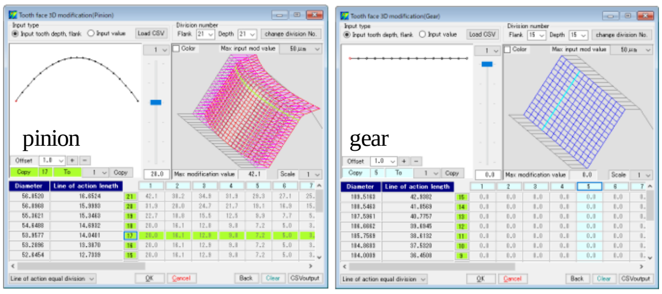


Fig.45.76 profile modification

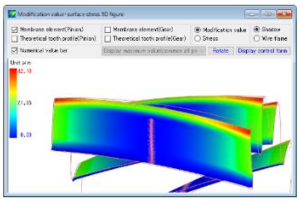


Fig.45.77 tooth surface element

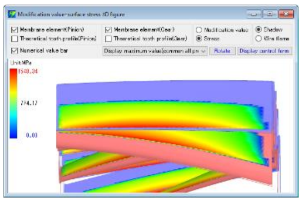


Fig.45.78 σ_{Hmax}=1548MPa

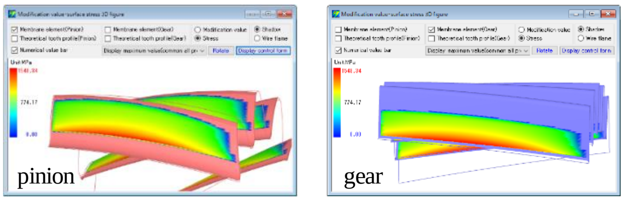
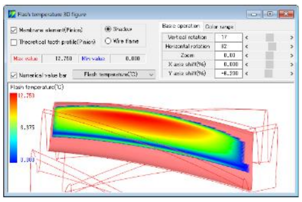
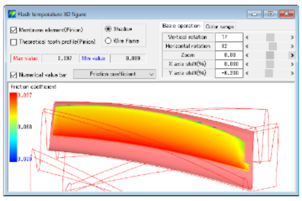


Fig.45.79 tooth surface stress (σ_{Hmax}=1548MPa)



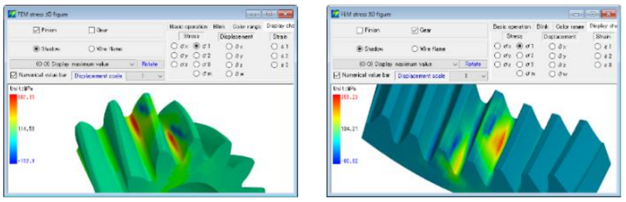
T_{fl}=12.8(℃)

Fig.45.80 flash temperature



μ_{max}=0.097

Fig.45.81 friction coefficient



(a) pinion, σ_{1max}=382MPa (b) gear, σ_{1max}=355MPa

Fig.45.82 maximum principal stress,

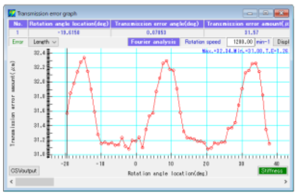


Fig.45.83 transmission error

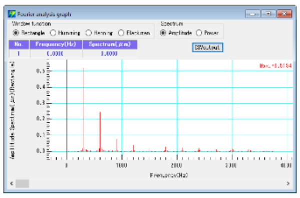


Fig.45.84 Fourier analyses

※1 The tooth shape given in Fig.45.15 and the tooth profile generated by optimal tooth surface modification can be file output (3D-IGES), so it can be used for analysis and processing.

※2 Please see Appendix [I] for stress analysis examples, Appendix [J] for transmission error analysis examples and Appendix [K] for examples of power loss analysis.