

STUDY FOR THE VERIFICATION OF THE TOOTH PROFILE ACCURACY OF THE AUTOMATIC GEAR DESIGN PROGRAM

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Abstract

The gear is a major mechanical element for the power transmission between two adjacent axes. Even though tooth profile of the gear is made of involute and cycloid curve, involute curved gear is generally used by the easiness of the fabrication and assembly. There are lots of studies for the gear design but mostly weighted toward to the drawing production and two dimensional modeling. And because the exclusive three dimensional gear design program is costly high, it is only used at the very confined fields. In this study, we developed automatic gear design program to create three dimensional model and gear profile of the spur and helical gear with involute tooth profile by using user development program named Visual LISP on the AutoCAD and compared each gear tooth profile which is created by automatic design program and commercial program named KissSoft, Inventor utilizing exclusive reverse engineering program named RapidForm XOV and performed gear fabrication through wire cutting electric discharge machining and after that, we compared gear measured data which was made by three dimensional scanner and made by the fabricated gear to check accuracy of the gear profiles. And also checked interference and undercut of the gear tooth by using gear driving motor.

Keywords: ADP (automatic design program), Involute curve, Spur Gear, 3D Scanner, W-EDM (wire electric discharge machining)

1. Introduction

All The gear is a major mechanical element for the power transmission between two adjacent axes. Even though tooth profile of the gear is made of involute and cycloid curve, involute curved gear is generally used by the easiness of fabrication and assembly [1]. Now, there are lots of studies for the gear design but mostly weighted toward to the drawing production and two dimensional modeling [2, 3]. And because the exclusive three dimensional gear design program is costly high, it is only used at the very confined fields.

Also the function of the gear design which to be provided from the general three dimensional modeler is only used to simply

check assembled shape of the gears by creating similar shape with the involute curve instead of creating exact gear tooth profile.

It needs lots of costs and times to fill and train manpower for the three dimensional modeling of the products. Accordingly it is introduced methods to make easy use of the three dimensional model for the products. Typical method is the buildup of the automatic design program to the necessary products and mechanical elements. By using user development program named Visual LISP on the AutoCAD which is now used to public, it is possible to buildup library of the automatic design program for the mechanical elements [4~7]. It has advantage to create three dimensional model of the mechanical elements by the beginner just to input minimum numerical values necessary to create mechanical elements and it is expected that lots of practical applications would be made at the production fields.

In this study, we developed automatic gear design program to create three dimensional model and gear profile of the spur and helical gear with involute tooth profile by using user development program named Visual LISP on the AutoCAD and compared each gear tooth profile which is created by automatic design program and commercial program named KissSoft, Inventor utilizing exclusive reverse engineering program named RapidForm XOV and performed gear fabrication through wire cutting electric discharge machining and after that, we compared gear measured data which was made by three dimensional scanner and made by the fabricated gear to check accuracy of the gear profiles. And also checked interference and undercut of the gear tooth by using gear driving.

2. Automatic gear design program

2.1. Automatic gear design program by using Visual LISP

To develop automatic gear design program, we used user development program named Visual LISP on the AutoCAD and in the Fig.1 we showed process to develop automatic gear design program. First, select object to perform automatic design and decide specification for the object by referencing ISO, JIS

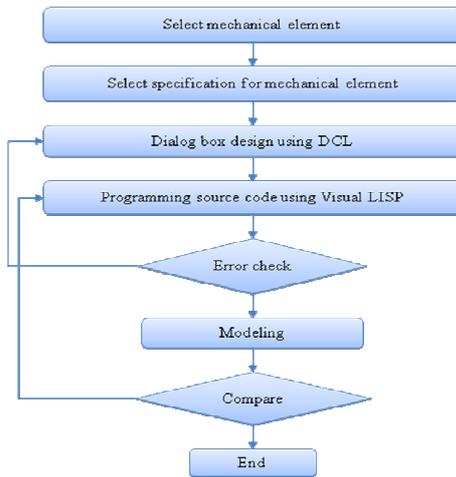


Fig. 1: Flowchart for automatic design program

and KS etc. And then construct dialog boxes using DCL (Dialog control language). In this case dialog boxes are composed according to the kinds of the object, number of the input element and level of difficulty. The purpose of the dialog boxes is that to make user possible to input design variables and deliver it by the LISP code so as to make accurate modeling.

And prepare program source code for the Visual LISP by referencing DCL code and check errors throughout debugging. When there are errors, primarily it need to check whether input values are delivered with exact variables name at the dialog box by using DCL and should find out errors. And when there are no errors call LISP file made on the AutoCAD and perform modeling. The automatic design program is finished if there is no errors in comparing shape between realized by the AutoCAD and selected object. The most important area of the automatic design program is to make decision of the modeling method and generable mathematical and geometrical algorithm should be applied to create new model.

2.2. Gear design methods

2.2.1. Tooth profile of the spur gear

The tooth profile of the gear is composed of module, pressure angle, backlash and clearance etc and these values are decided by the user input values on the automatic design program. The pressure angle means the angle which is made between the common line tangent to the both two gear pitch circles and line of action for a pair of the mating gears. Standard pressure angle is composed of 14.5°, 20° and 27°, but 27° angle is generally not in use [1]. Generally for the gears which have involute tooth profile, mutual movement is only possible when pressure angle and size of the tooth, that is module, is same for the mating gears. And the geometrical condition to create curve of the gear tooth profile is that two gears should have constant angular speed ratio for the all mating positions. To meet these conditions, it is permitted to have speed difference of the tangential way between mating surfaces of the two moving gear tooth (The speed difference of the tangential way appears as slippage between two gear teeth) but speed at the perpendicular way for the two gear teeth should be same. When there is a speed difference at the perpendicular way against to the gear tooth surface, it means that the tooth surface of the two gears will be separated each other or one of the gear tooth surface will be snuggled in to the other gear tooth surface. So, speed of the tangential way between two mating surfaces should be kept same. These matters are shown in

Fig. 2 in detail. In the Fig. 2, the perpendicular way speed of the two gear teeth should be same and following equation is established.

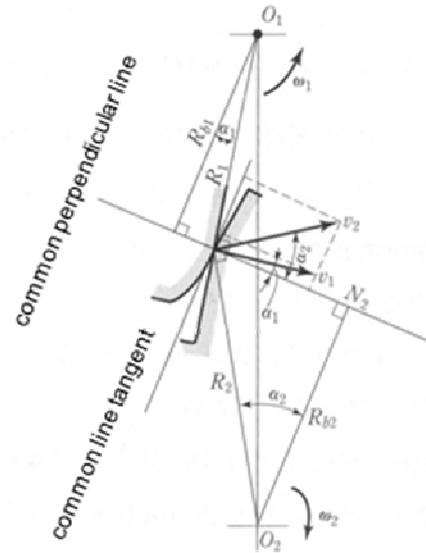


Fig. 2: Necessary condition of the involute curve

$$v_1 \cos \alpha_1 = v_2 \cos \alpha_2 \quad (1)$$

v_1 : Rotating speed to the perpendicular way at the mating point of the gear #1.

v_2 : Rotating speed to the perpendicular way at the mating point of the gear #2.

α_1 : Pressure angle of the gear #1.

α_2 : Pressure angle of the gear #2.

Speed is calculated by multiplying rotational radius by rotational angular speed and can be expressed as follows.

$$v_1 = R_1 \omega_1 \quad (2)$$

$$v_2 = R_2 \omega_2 \quad (3)$$

R_1 : Rotational radius of the gear #1.

R_2 : Rotational radius of the gear #2.

ω_1 : Rotational angular speed of the gear #1.

ω_2 : Rotational angular speed of the gear #2.

When we calculate angular speed ratio (ϵ) between two gears by substitute the equations (2) & (3) to the equation, it will be as equation (4).

$$\epsilon = \frac{\omega_2}{\omega_1} = \frac{R_1 \cos \alpha_1}{R_2 \cos \alpha_2} \quad (4)$$

When we use principle of the similar figure for the two right triangles $\triangle O_1 N_1 P$ and $\triangle O_2 N_2 P$,

$$\epsilon = \frac{\omega_2}{\omega_1} = \frac{R_1 \cos \alpha_1}{R_2 \cos \alpha_2} = \frac{R_{b1}}{R_{b2}} \quad (5)$$

R_{b1} : Distance from the gear #1 to the common perpendicular line.

R_{b2} : Distance from the gear #2 to the common perpendicular line.

As we know from the equation (5), to get the same perpendicular way speed against to the tooth surface and to get the constant angular speed ratio, the vertical line against gear tooth at the

mating point of the two gears should pass one fixed point. And this point is called as the pitch point and the radius from the center of the gear to the pitch point is called as the pitch circle [1].

2.2.2. Mathematical algorithm of the involute curve

As shown in the Fig. 3, when unwind thread from the point P to point P' with tightly pulling it which is wound on the cylindrical tube that roles as the base circle diameter, the trace of a thread point is an involute curve. We call cylindrical surface of the tube as a base circle diameter and the formed tooth profile along the involute curve is called as an involute tooth profile [1, 8, 9].

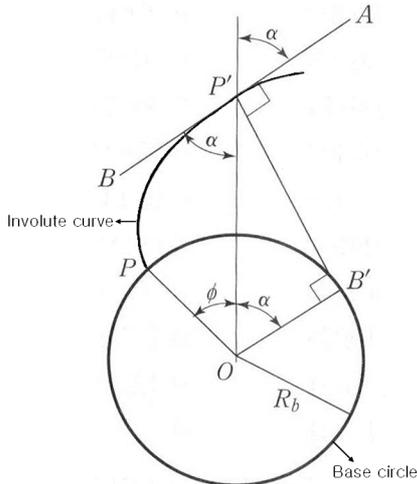


Fig. 3: Involute function

The thread length $\overline{PB'}$ after unwinding the thread is same as the arc of the circle PB' that is the length of the thread which is wound to the base circle diameter before it is unwound.

$$\overline{PB'} = R_b(\phi + \alpha) = \overline{PB'} = R_b \tan \alpha$$

$$R_b(\phi + \alpha) = R_b \tan \alpha \tag{6}$$

R_b : Radius of the base circle diameter
 Φ : Involute function of the tool pressure angle (α)

When we arrange above equation (6), we can get following mathematical relation. Each Φ is called as an involute function of the tool pressure angle (α) and indicates as $\text{inv } \alpha$. So,

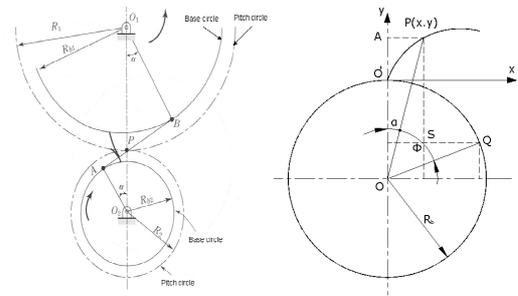
$$\phi = \text{inv } \alpha = \tan \alpha - \alpha \tag{7}$$

As shown in the Fig. 4 (a), the common perpendicular lines established at the mating point of the tooth meet each other and pass the pitch point and so, it satisfy theory of Camus. Eventually we know that pressure angle and tooth size of the involute tooth profile gear should be same.

In the Fig. 4 (b) when thread is unwound from the base circle diameter (R_b) and if we call the coordinates made by the one point of the curve $\square POQ$ as Φ and $\square O'OP$ as α , the (x, y) coordinates of the point P is obtained as the equation (8).

$$x = R_b \sin(\phi + \alpha) - R_b(\phi + \alpha) \cos(\phi + \alpha)$$

$$y = R_b \cos(\phi + \alpha) + R_b(\phi + \alpha) \sin(\phi + \alpha) - R_b \tag{8}$$



(a) Principle of action for involute curve (b) Coordinate of involute tooth involute curve

Fig. 4: Involute curve

2.3. Automatic gear design program

Fig. 5 is the main dialog box of the automatic gear design program which is developed by this study. And Fig. 6 shows flow chart to use the automatic gear design program which is developed by this study. To perform gear design, first select kinds of the gear to be designed through the button located at the upper part of the dialog box. The degree of the active windows for the input becomes differ according to the kinds of the gear. And when press OK button after input major dimensions such as pressure angle, number of the tooth and module etc, the three dimensional or two dimensional designs become realized.

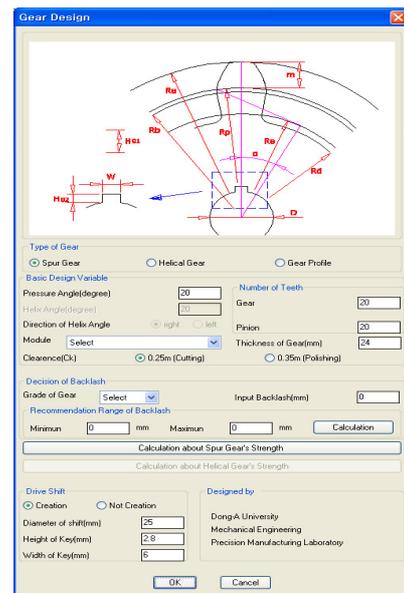


Fig. 5: Dialog box of automatic design program for creating of 3-D spur and helical gear

The automatic gear design program which is developed by this study is made possible to create three dimensional gear designs for the spur and helical gears which are mostly used in the gear designs. And when it needs to use only gear tooth profile, we composed program to create two dimensional profiles for the easy use of it.

In this program we made standard value of the modules for the cylindrical gear with involute tooth profile as 1 & 2 and 3 selects it by separated series [10]. Also we made program for the clearance as 0.25m (m: Module) for the cutting and 0.35m for the grinding to make selection from both of it and according to this result, value of the clearance can be calculated and input to the program. And for the backlash of the gear can be directly put in to the program by the user expressing minimum and maximum.

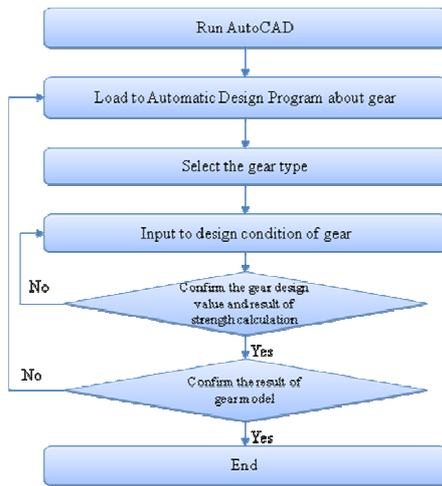
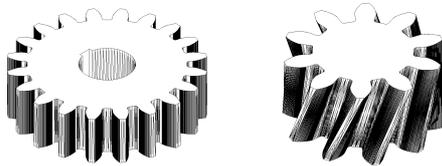


Fig. 6: Flowchart to create gear model for automatic design program

Values on the program which meet condition of the gear according to the pitch circle diameter, module and grade of the gear (0~8grades) [9, 10, 11, 12]. Also the user can select creation of the key home and hole according to the need which is used to assemble gear to the driving shaft and enter values on the program. When input above conditions to the program and press OK button, the user can find out gear shape which is requested within a few seconds to dozens of seconds.

Fig. 7 shows three dimensional shape of the spur and helical gear which are created by the automatic gear design program developed by this study. The basic design values of the spur and helical gear are shown in Table 1.



(a) Spur gear (b) Helical gear

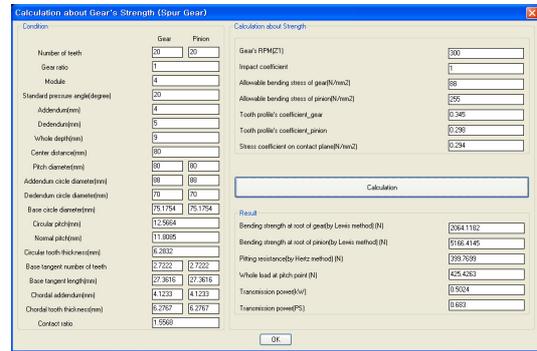
Fig. 7: Shape of 3-D modeling using automatic gear design program

Table 1: Basic value for 3-D gear modeling using automatic design program

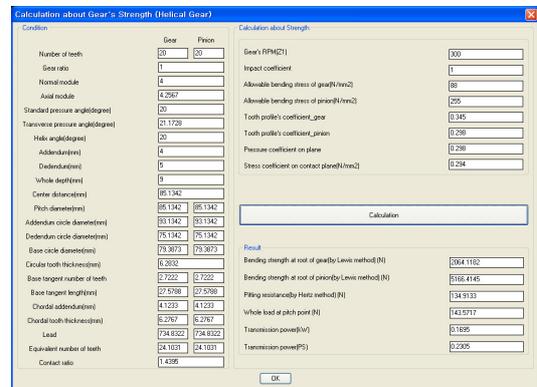
Value	Spur gear	Helical gear
Module	4	2.5
Pressure angle(°)	20	20
Helix angle(°)	-	25
Number of Teeth	20	10
Grade of gear	0	0
Backlash(mm)	0.07	0.045
Clearance(mm)	0.25m = 1	0.35m = 0.875

Dialog box for the design values and strength calculation of the spur and helical gear is shown in Fig. 8. This dialog box can be seen when press strength calculation button of the main dialog box which is shown in Fig. 5 after entering necessary precedent conditions on the program. On the left side of the main box, the calculated basic design values and mating ratio of the gear to be

seen for the now design wanted gear based on the setting values at the main dialog box. And for the right upper side of the dialog box we provide input area to enter constants and conditions to the program for the calculation of the strength and the calculated value is shown on the bottom side of the screen.



(a) Dialog box for the strength calculation of the spur gear



(b) Dialog box for calculation about helical gear strength
Fig. 8: Dialog box for calculation about gear's strength

3. Compare with commercial program

3.1. Creation of the gear tooth profile using commercially available program

The software in relation to the gear design and analysis are introduced in variety. The typical software in relation to the gear design is the KissSoft which is developed and commercially available. It is possible to analysis gear by applying ISO, AGMA, DIN specifications and has function to design and analyze cylindrical gear and bevel gear etc. The general commercially available modeling programs are provided design method for the gears which is suitable for each one's methods. The automatic gear design program which is developed by this study is based on the AutoCAD of the Autodesk Company. Even though the AutoCAD does not carry their own module for the gear design but for the Inventor of the Autodesk Company, the design module for the gear design is carried and used. So, we want to confirm the accuracy of the tooth profile of the gear which is created by the automatic gear design program developed by this study with the one which are created by the KissSoft and Inventor.

The basic conditions for the creation of the tooth profile of the gear is pressure angle, module, number of tooth, clearance and gear grade etc and the used conditions in this study are as Table 1 shown on the above. Fig. 9 shows two dimensional gear tooth profile which is created by the KissSoft and three dimensional gear tooth profile which is created by the AutoCAD by using gear

tooth profile stored as dxf file. Fig. 10 shows main screen to create gear shape at the Inventor. It is possible to input pressure angle, module, number of tooth etc and it is possible to create normal, low and high height tooth by adjusting addendum. And it is possible to enter clearance on the program but it is not possible to enter backlash according to the accuracy grade of the gear.

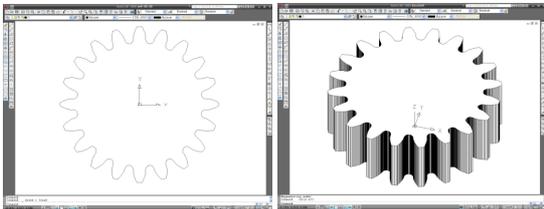


Fig. 9: 2D gear tooth profile and 3D model created by dxf file using KissSoft program

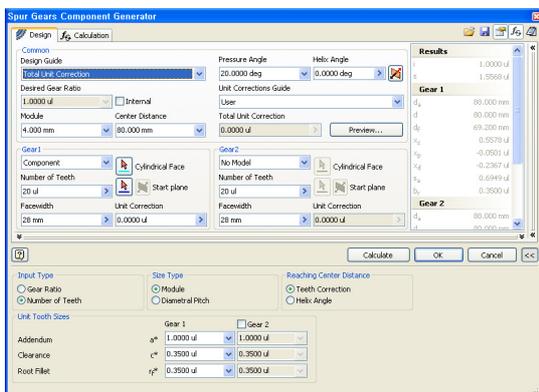


Fig. 10: Main screen of Inventor to create 3D model

Fig. 11 shows gear tooth profile created by the Inventor. When we review overall shape, it looks like similar with the gear but shape at the end of the tooth area and involute gear tooth curve is different with gear shape.

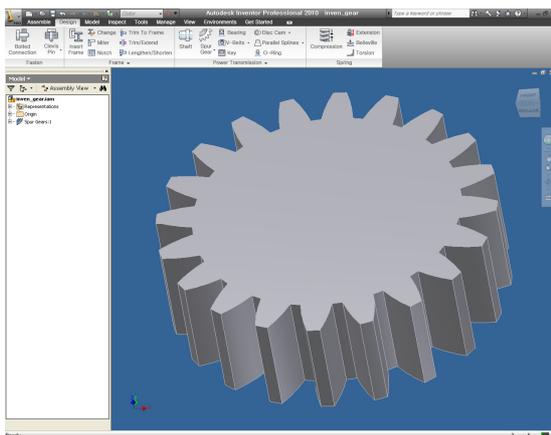


Fig. 11: Result of created gear using Inventor

3.2. Comparison between automatic design program and commercial program

To compare the automatic gear design program which is developed by this study and the commercially available program, we used the exclusive reverse engineering program named Rapid-Form XO.V. First, using the gear tooth profile as a basic data which is created by the exclusive professional purpose gear software program named KissSoft, we compared the gear tooth profile created by the automatic gear design program and the gear tooth profile created by the Inventor. For this purpose, we

converted basic data to the stp file type and converted comparison data to the stl file.

Fig. 12 shows the comparison result between the KissSoft data and Inventor data for the created gear profiles and indicates differences at the gear tooth profile. The measured positions are selected 9 points from the outside diameter to the involute curve and we can observe that the errors occur at all surfaces of the teeth profile. When we review sectional shapes of these points we found that the creation of the gear shape by the Inventor does not create involute gear tooth profile but only creates similar shape with the gear tooth profile and realizes simple operational mechanism and it can be used for presentation purpose by creating model in a quick time.

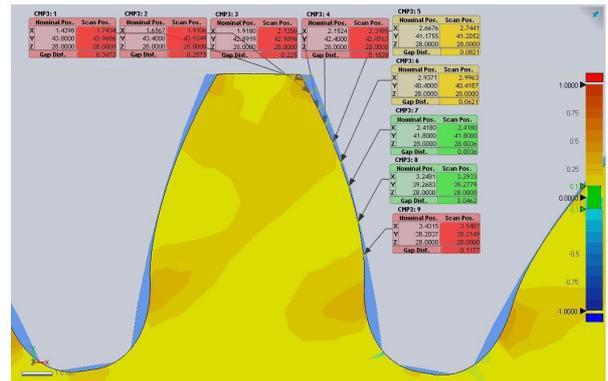


Fig. 12: Error on gear tooth profile (KissSoft vs Inventor)

Fig. 13 shows comparison results of the created gear shape by the KissSoft and the created gear shape by the automatic design program developed in this study by the using of the Visual LISP. And it shows the differences at the gear tooth profile. The measuring positions are decided same as the measuring positions shown in the Fig. 12 and we can see the measured errors at the front of the gear tooth profile are from 0.0001mm to 0.0085mm. So, we know that gear tooth profile of the two data nearly coincide with each other and the error shown in this data is considered as general machining tolerances. And it is considered that the reliability for the gear tooth profile is sufficient. Fig. 14 shows graph of the error results for the involute gear tooth profile. In case for the gear created by the Inventor the maximum error is 0.3473mm according to the measured position and the errors tend to be reduced when measured points become close to the no. 7 position which is close to the pitch circle. In this result, we know that in case for the Inventor, it creates similar gear tooth profile by using arbitrary curve based on the pitch circle when creating tooth profile.

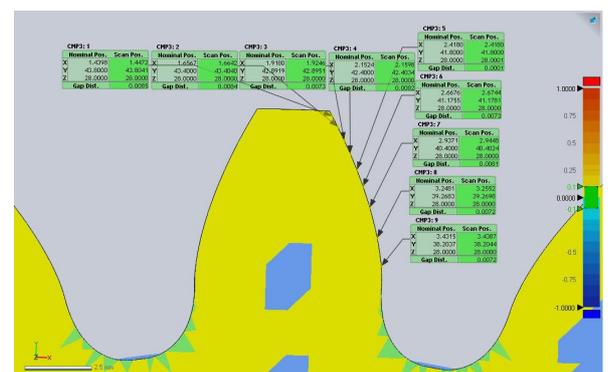


Fig. 13: Error on gear tooth profile (KissSoft vs gear automatic design program)

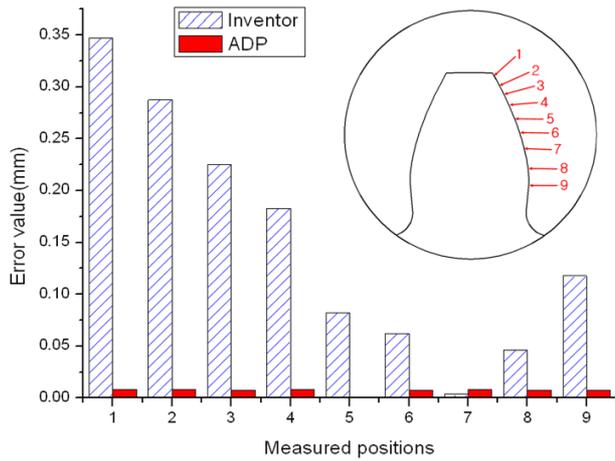


Fig. 14: Comparison with measured error on gear models (Inventor vs ADP)

4. Fabrication of the spur gear using wire cutting electric discharge machining

4.1. Overview of the wire cutting electric discharge machining

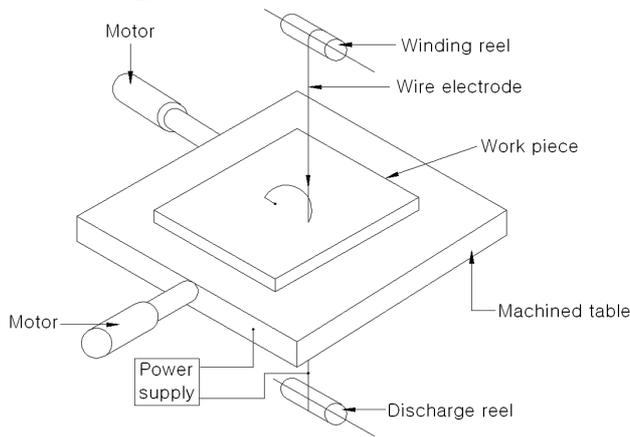


Fig. 15: Principle of W-EDM

Electric discharge machining, EDM is a part of the electrical removing machining and perform machining by using discharge energy from the spark which are partially arose between electrode and product to be machined [12]. Generally speaking, when using wire as an electrode we call it as an wire cutting electric discharge machining (W-EDM). Fig. 15 shows basic principle for the wire cutting electric discharge machining.

4.2. Fabrication of the spur gear and inspection of the prototype using 3D scanner

Fig. 16 shows the wire cutting electric discharge machine used in this study and three dimensional scanners



Fig. 16: Manufacturing machine to process gears (W-EDM, AQ750L) and Photography of Reverse Engineering System (StereoSCAN^{3D})

To verify gear fabricated by the wire cutting electric discharge machining, the gear was measured by three dimensional scanners and compared it with CAD data. Fig. 17, 18 shows measured errors graph at the gear tooth profile by comparing the measured data of the gear with 20° pressure angle, module 4, 20 teeth that is fabricated by the wire cutting electric discharge machining and CAD data created by the automatic design program.

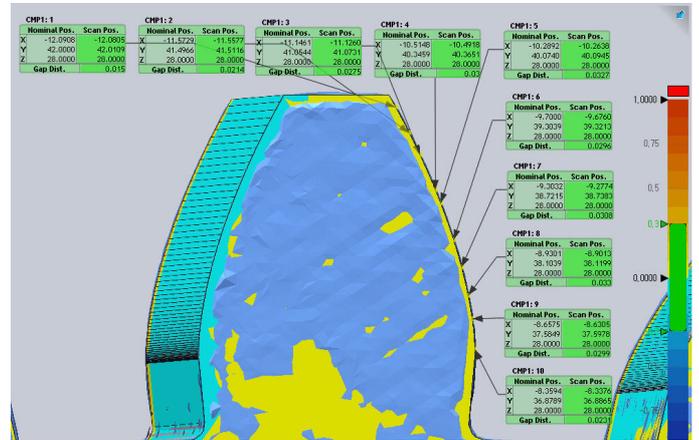


Fig. 17: Comparison of measured data and CAD data on tooth profile

The measured positions was decided 10 positions at the surface of the gear tooth profile and compared errors between the CAD data and measured data. It was shown that errors at the gear tooth profile are from 0.015mm to 0.033mm. And it is shown that errors happen least at the end area of the gear tooth and errors increase gradually by the machining of the tooth shape. When performing profile machining using wire cutting electric discharge machining, the tension of the wire which roles as the electrode vary according to the machining direction and consider as the cause of the errors by the change of the tension and vibrations [13~15]. Also we can predict that the change of the electric discharging voltage and change of the surface area of the gear by the electrolyze effect of the water also effect to the machining accuracy.

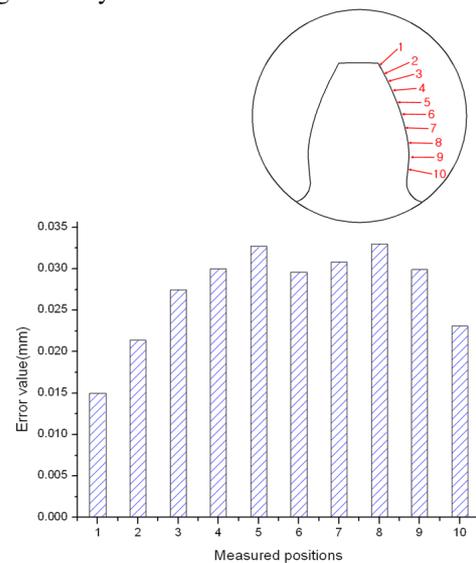


Fig. 18: Graph for measured error of spur gear by W-EDM

4.3. Check interference and undercut of the gear

Interference of tooth means the phenomenon that the gears cannot rotate because of the interference between end of the

tooth of the one gear and the root of the other gear when a pair of the gear rotates with mating each others. The reason is that for the involute gear, the involute gear tooth profile at inside of the base circle diameter is not created. The undercut means the cutting phenomenon through the path of the root surface of the pinion by the end of the gear tooth of the opponent gear when there is an interference between the gear teeth and end of the teeth of the pinion gear become thin and make weak in strength of the teeth as well as the cause of shortening of the mating length [1].

In this study, we checked interference and undercut of the gear tooth using the gear with 20° pressure angle, module 4 and 20 teeth that is fabricated by the wire cutting electric discharge machining. Using the gear driving motor, we rotated a pair of the same size gears and inspected interference of the gear teeth. Fig. 19 shows the testing devices to check interference of the teeth. It is composed of the two shafts and one of it is assembled to the driving motor and torque converter is installed to the other side. The major purpose of this device is to check interference of the gear teeth, these gears were driven with no load condition.

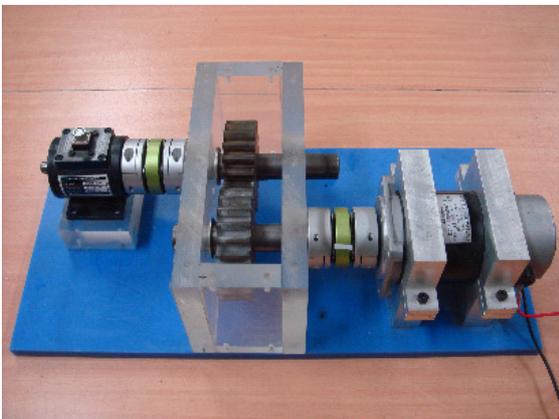
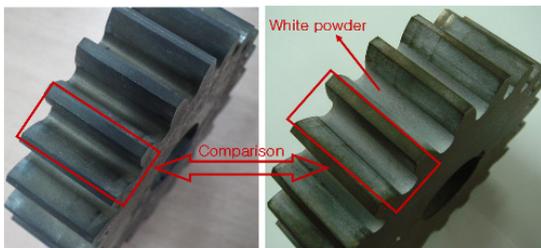


Fig. 19: Experimental equipment for interference of tooth



(a) Before experiment (b) After experiment

Fig. 20: Experiment result for interference of tooth and undercut

Where to check interference at the end of the gear teeth profile, we applied white powder to the surface of the gear teeth profile. Fig. 20(a) shows surface of the gear tooth profile before applying white powder and Fig. 20(b) shows surface of the pair of the gear teeth profile after driving gears with white powder is applied for the both of the gears.

On the Fig. 20(b) which shows gear surface after the test, we find out that some of the white powder is removed at the gear tooth profile where gear tooth rotate with engaging each other, but white powder at the inside of the rectangular mark which is a root of the gear tooth remains as it is. Throughout the result of this study, we confirmed that there was no interference and undercut at the root area of the gear tooth which was designed using automatic gear design program and secured reliability for the gear design values.

5. Conclusions

In this study, we made following conclusions.

1. We confirmed reliability of the gear tooth profile made of the automatic design program throughout comparison of the gear shape made by the automatic design program and by the KissSoft, Inventor.
2. When we performed gear running test using gear driving motor, we confirmed that there is no interference and undercut of the gear which is created by the automatic gear design program and fabricated by the wire cutting electric discharge machining.

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