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PROCESS ANALYSIS FOR INTERNAL GEAR GRINDING

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ABSTRACT

The internal gear grinding machine, ZI20A is the first of its kind that is applicable for mass production of internal gears. It is suitable for grinding planetary gears, heat-treated internal or external gears at high speeds with high accuracy. One of the features of this machine is its ability to grind stepped workpieces. In case of stepped workpieces, it is difficult to determine the axial stroke required to achieve proper grinding of the entire tooth surface without causing any interference of the stepped region with the machine parts or grinding wheel. During the grinding test of such workpieces, sometimes the tooth flank remains unground at the ends due to inadequate axial stroke. A new simulation tool has been developed to visualize and analyse the internal gear grinding process. Using this simulation tool, the axial stroke required for grinding can be estimated without performing actual grinding tests.

INTRODUCTION

In recent years, the demand for precision machining of planetary gears has increased due to the requirement of reduced noise and vibration in automotive transmissions. For ring gears (one of the components of a planetary gear system), the conventional method of finishing has been gear shaping or helical broaching followed by heat treatment. To meet the increasing requirement of the aforementioned demand, mass produced planetary gear systems, must be hard gear finished after heat treatment with high accuracy and efficiency. Mitsubishi's internal gear grinding machine, ZI20A provides the solution for efficient hard gear finishing of internal ring gears. This machine has been designed specifically for the mass production of automotive internal ring gears using a multi-threaded vitrified grinding wheel. By using a vitrified CBN (Cubic Boron Nitride) grinding wheel, the manufacturing cost per workpiece can be reduced as compared to using a conventional aluminium oxide or silicon carbide grinding wheel. The ZI20A machine uses the same surface of the grinding wheel at all times, for continuous grinding. Hence, the load on the flank of threaded grinding wheel is quite high and there is a greater possibility for abrasion of the grinding wheel surface.

Grinding of gears with interfering contours or stepped workpieces is a challenge due to the risk of interference between the workpiece and grinding wheel or the machine tool component. From previous grinding test results on ZI20A, it has been observed that the bottom part of the tooth flank remains unground despite changing grinding conditions. This is observed to be true especially in case of stepped workpieces with interfering contours, where the axial stroke is limited because of interference of the grinding wheel with the protruding part of the adjacent step in the workpiece. In such cases, it is difficult to determine the axial stroke and crossed axes angle required to achieve proper grinding of the entire tooth surface. One of the methods to analyse the internal gear grinding process is by using three-dimensional (3D) CAD. The 3D models of internal gear and grinding wheel are created and their axes are aligned to make an angle equal to the crossed axes angle. The grinding wheel is rotated by a very small angle and the interfering region on the internal gear is removed. Consequently, the model of the internal gear is regenerated. The above process is repeated in a loop using a macro program. Such kind of simulation using 3D-CAD is extremely time consuming and computationally intensive.

Grinding tests are have been carried out by changing the specifications of the grinding wheel (facewidth, number of threads, outer diameter) or crossed axes angle, in order to check their influence on the grinding process. It involves manufacturing of a new grinding wheel for every new condition which results in costs and loss of time. Analysis of the internal gear grinding process based on a numerical approach would save time and cost. Hence this new simulation tool has been developed.

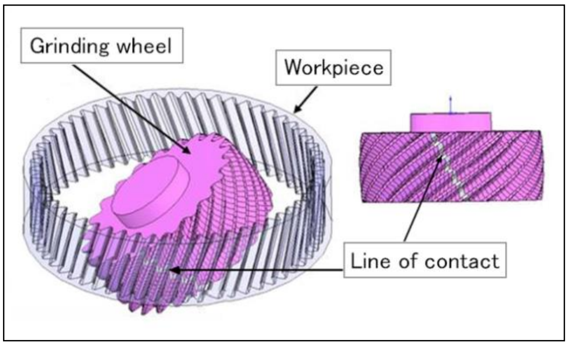


Fig. 1 Analysis using 3D-CAD

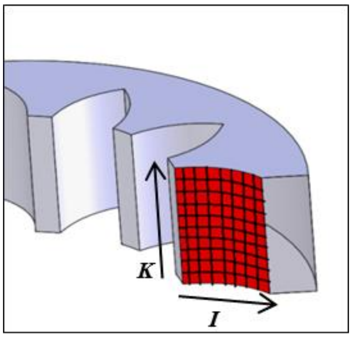


Fig. 2 Grid points on a tooth surface (Left flank)

METHOD

The simulation tool is based on numerical calculations of the following:

a) Involute tooth profile of the internal gear
b) Profile of the flank of threaded grinding wheel
c) Clearance between the workpiece tooth and flank of threaded grinding wheel.

The coordinates of a single tooth of workpiece and a single flank of threaded grinding wheel are estimated using an iterative numerical algorithm. Using these values and the simulation conditions, the clearance between the workpiece tooth and flank of threaded grinding wheel is estimated numerically at all points on the tooth flank (Refer Fig. 2 and Fig. 3).

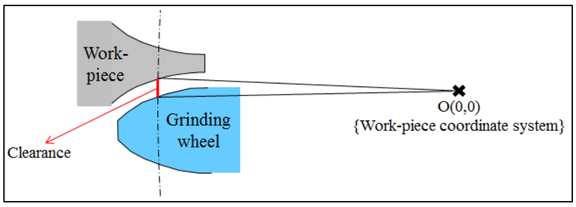


Fig. 3 Clearance between workpiece tooth and flank of threaded grinding wheel

SIMULATION CONDITIONS

The workpiece and grinding wheel data, enlisted in Table 1 are the necessary input conditions for the simulation. Using these, the coordinates of a single tooth of workpiece and single flank of threaded grinding wheel are estimated using an iterative numerical algorithm. Apart from the workpiece and grinding wheel data, the grinding simulation conditions such as the crossed axes angle and depth of cut for each grinding pass can be specified (see Table 2). Using these input conditions, the clearance between the workpiece tooth and flank of threaded grinding wheel is estimated numerically at all points on the tooth flank. The simulation conditions enlisted in Tables 1 and 2 are of a standard automotive internal ring gear. The results presented in this paper are for the above simulation conditions.

Table 1 Workpiece and Grinding Wheel Data

Workpiece data	
Normal module, m	1.5
No. of teeth, Z_w	60
Pressure angle, α_{nw}	21°
Helix angle, β_w	25°
Facewidth, B_w	30 mm
Root diameter, d_{wr}	110 mm
Grinding wheel data	
Tip diameter, d_{gt}	60 mm
Facewidth, B_g	20 mm
No. of starts, Z_g	23
Helix angle, β_g	47°

Table 2 Grinding simulation conditions

Grinding simulation conditions	
Crossed axes angle, Σ	22°
Depth of Cut (1st pass)	0.03 mm
Depth of Cut (2nd pass)	0.06 mm
Depth of Cut (3rd pass)	0.06 mm

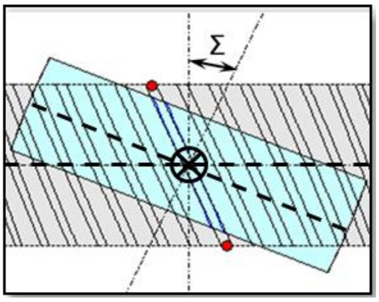


Fig. 4 Initial condition when center of grinding wheel is at the same height as center of workpiece

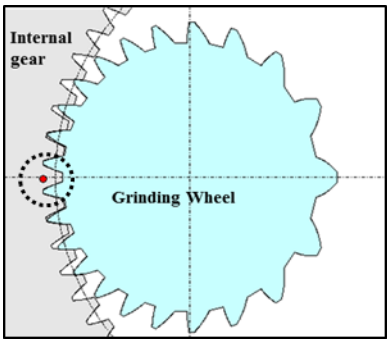


Fig. 5 Initial condition of workpiece tooth and flank of threaded grinding wheel in contact

The initial condition of the simulation is graphically shown in Fig. 4 and Fig. 5. Fig. 4 shows the position when the center of grinding wheel is at the same axial height as center of workpiece. In the simulation tool, this position is referred to as the position where the grinding wheel height is zero. The axial stroke of the grinding wheel in the upward and downward direction is calculated with this position as the datum. Fig. 5 shows the initial condition of the workpiece tooth in contact with the flank of threaded grinding wheel. The simulation results are for the single tooth of the workpiece and grinding wheel which are in contact (see region encircled with dotted line in Fig. 5). In this simulation tool, this position is where the angle of rotation of the workpiece is zero. The contact condition between the workpiece and flank of threaded grinding wheel is changed when the workpiece is rotated in the clockwise or anti-clockwise direction with this position as the datum.

SIMULATION RESULTS

Region of Contact at a Given Instant

Using this simulation tool, the contact condition between a single flank of the threaded grinding wheel and single tooth of the workpiece can be graphically represented using the calculated values of clearance at each point of the flank. The region of contact between workpiece tooth and flank of threaded grinding wheel can be estimated for a given instant, for example, for a certain height of the grinding wheel and for a certain angle of rotation of the workpiece. Whenever the value of clearance at a given point is zero, it means that contact takes place between the workpiece and grinding wheel at that point. When the value of clearance at a point is negative, it means that material is removed from the workpiece tooth at that point.

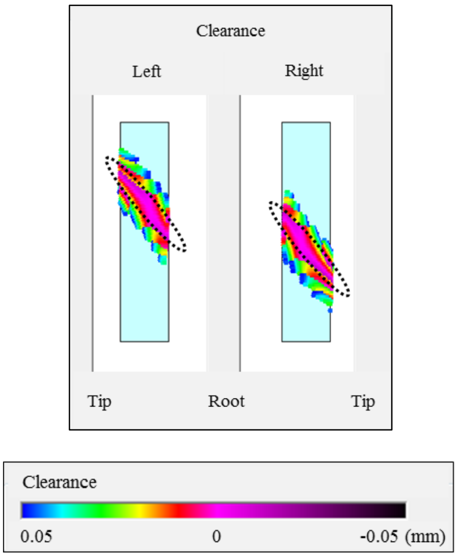


Fig. 6 Region of contact at a given instant
(Viewed on flank of threaded grinding wheel)

Fig. 6 shows the region of contact between the workpiece tooth and flank of threaded grinding wheel at an instant when height of the grinding wheel is zero and angle of rotation of the workpiece is zero (at initial condition, Fig. 4 and Fig. 5). The result will change when the height of the grinding wheel is changed or if the workpiece is rotated. The clearance condition can be viewed on the surface of the flank of threaded grinding wheel or the workpiece tooth at a given instant of time. Fig. 6 shows the region of contact viewed on the surface of the flank of threaded grinding wheel flanks (rectangular region). The region of contact on the left flank and right flank are shown and the location of the tip of the flank and its root are indicated in the figure. A coloured contour on the flank of threaded grinding wheel is used to represent the amount of the clearance at every point on its surface. In this simulation result, pink colour indicates zero or negative clearance while blue, green, yellow and red colours indicate positive clearance. In Fig. 6, the region inside the dotted line is the region where the clearance is zero (region of contact). The region outside the dotted line is where the clearance values are between 0 to 0.05 mm.

Frequency of Contact

Using this simulation tool, the frequency of contact between workpiece tooth and flank of threaded grinding wheel can be qualitatively estimated from the clearance values at every point on the tooth surface. Frequency of contact at a given point is defined as the number of times contact takes place between the workpiece and grinding wheel at that point. To obtain the simulation result of frequency of contact, the workpiece is rotated by very small increments and the clearance between the grinding wheel and workpiece tooth is calculated at every point on its surface for each angle of rotation. Furthermore, the grinding wheel is moved in the axial direction by small increments to traverse along the entire facewidth of the workpiece. The clearance condition is estimated for every position of the grinding wheel. This operation is carried out in a loop to cover the entire facewidth of the workpiece such that the workpiece makes one full rotation in small increments for each axial location of the grinding wheel. Frequency of contact is not an absolute number but depends upon the simulation step size. For example, if the incremental angle of rotation of the workpiece is very small, or the incremental step of the grinding wheel motion in the axial direction is small, the frequency of contact is proportionately increased. However, its relative distribution on the flank will remain unchanged, which means that it will be possible to estimate which region has more frequency of contact and which has lower. A coloured contour on the flank of threaded grinding wheel is used to represent the frequency of contact at every point on the flank. In this result, blue region is where the frequency of contact is small, while green, yellow and red regions are ones where the frequency of contact is high, in increasing order. From this simulation result, we can qualitatively estimate the region in which frequency of contact is higher. This can help in predicting the region of the flank of threaded grinding wheel which is subjected to higher load and therefore has a higher possibility of abrasion.

Frequency of Contact after Each Grinding Pass

Based on the grinding simulation conditions in Table 2, the frequency of contact can be estimated for every grinding pass. Fig. 7 shows the frequency of contact of the tooth of the workpiece and flank of threaded grinding wheel at every point on its surface for each grinding pass. These results show the frequency of contact only for a certain pass. Subsequently, the cumulative frequency of contact of all passes until a certain pass will also be presented.

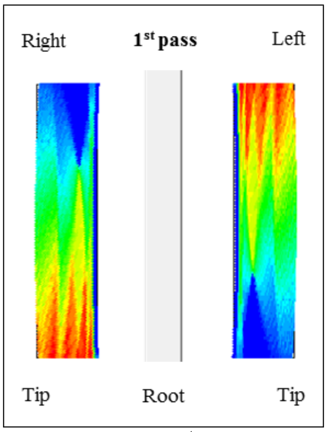


Fig. 7 (a) 1st Pass

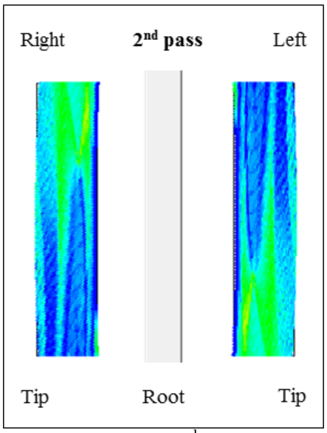


Fig. 7 (b) 2nd Pass

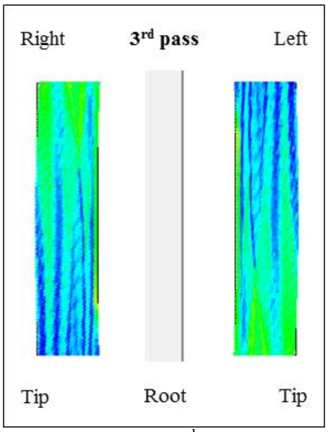


Fig. 7 (c) 3rd Pass

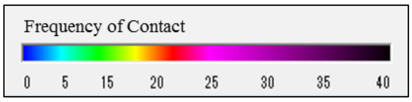


Fig. 7 Frequency of contact during a certain pass (Viewed on the flanks of threaded grinding wheel)

Cumulative Frequency of Contact

Cumulative frequency of contact is applicable for multiple grinding passes, where the total frequency of contact of the flank of threaded grinding wheel and workpiece tooth until that pass is counted. For example, in case of the 2nd grinding pass, the result is the combined frequency of contact of 1st pass and 2nd pass. Fig. 8 shows the cumulative frequency of contact after multiple passes between the tooth of the workpiece and flank of threaded grinding wheel at every point on its surface.

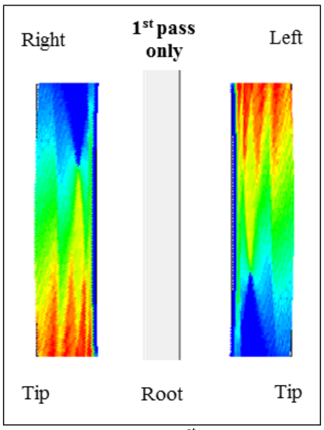


Fig. 8 (a) 1st Pass only

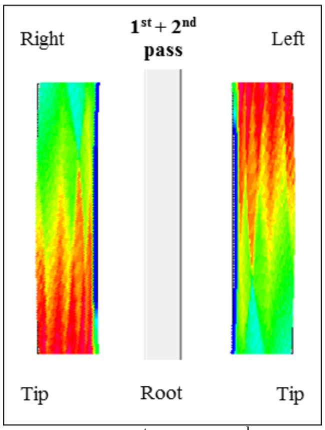


Fig. 8 (b) 1st Pass + 2nd Pass

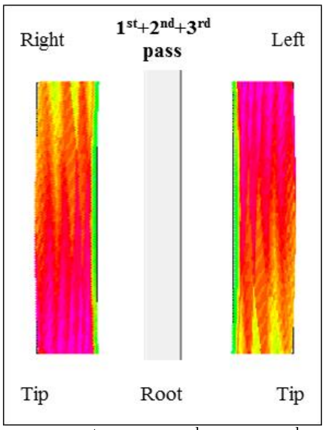


Fig. 8 (c) 1st Pass + 2nd Pass + 3rd Pass

Fig. 8 Cumulative frequency of contact after multiple passes (viewed on the flanks of threaded grinding wheel)

By viewing the result of the final grinding pass, we can check which region of the flank of threaded grinding wheel has the maximum frequency of contact. This would help in understanding the overall contact condition between the flank of threaded grinding wheel and workpiece tooth. It also helps to understand the distribution of load on the flank of the grinding wheel.

Analysis of Axial Stroke

Estimation of Axial Stroke Using Simulation

One of the applications of this simulation tool is estimation of the axial stroke required for grinding a workpiece. This is especially useful for workpieces with interfering contours or stepped workpieces where the available stroke is limited. Using the simulation results, the minimum axial stroke required in the upward and downward directions can be estimated. It has been shown that the contact condition between a single flank of the threaded grinding wheel and single tooth of the workpiece can be graphically represented using the calculated values of clearance at each point of the flank.

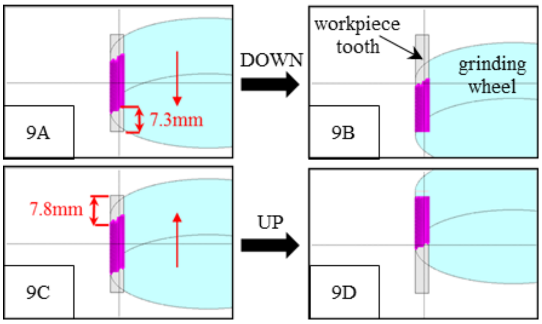


Fig. 9 Estimation of minimum axial stroke using simulation results

Fig. 9 shows the simulation result of contact condition after one rotation of the workpiece. The coloured region represents the points on the workpiece tooth which have had contact with the grinding wheel occurs between the workpiece and grinding wheel. The images (9A) and (9C) of Fig. 9, show the contact region for the position of the grinding wheel where its centre is aligned with that of the workpiece. To estimate the downward stroke, the grinding wheel is moved downwards until the bottom end of the workpiece tooth comes in contact with it as shown in image (9B). To estimate the upward stroke, the grinding wheel is moved upwards until the top end of the workpiece tooth comes in contact with it as shown in image (9D). The axial distance in the upward and downward directions can be calculated using the simulation tool. From Fig. 9, we can see that minimum axial stroke is 7.8 mm in the upward direction and 7.3 mm in the downward direction.

Comparison of Simulation Results with Axial Strokes used in Actual Grinding

The axial stroke used during actual grinding and its comparison with simulation results is explained below. The workpiece is a standard automotive internal gear with dimensions same as the simulation input conditions (Table 1). The axial stroke used for actual grinding is determined from simulation using 3D-CAD. During the actual grinding test, a small portion of unground material remained on the workpiece tooth (bottom end of the left side flank) as shown in the gear inspection chart (Fig. 10). The thickness of the unground portion is 4 microns while its width along the tooth flank is 6 mm.

The axial stroke of 11.5 mm used for actual grinding is insufficient because some material on the workpiece tooth remains unground. The minimum value of downward axial stroke obtained from simulation results is 7.3 mm. Due to the discrepancy in the values of stroke obtained from simulation results and actual grinding test, it can be understood that the above method of estimating the axial stroke using simulation is not enough. There is a need for additional reasoning in order to estimate the axial stroke more accurately. Hence, the effect of frequency of contact on the axial stroke estimation is considered.

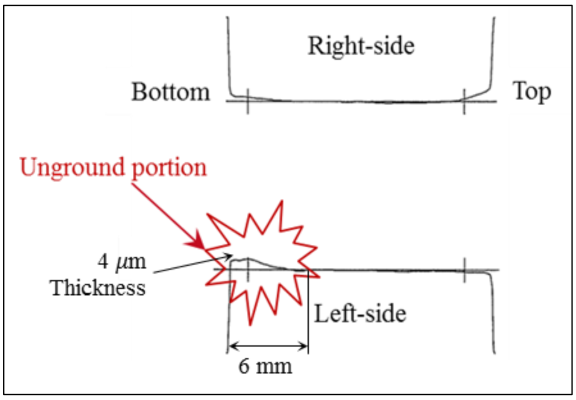


Fig. 10 Gear inspection chart (tooth profile) showing unground material on tooth flank

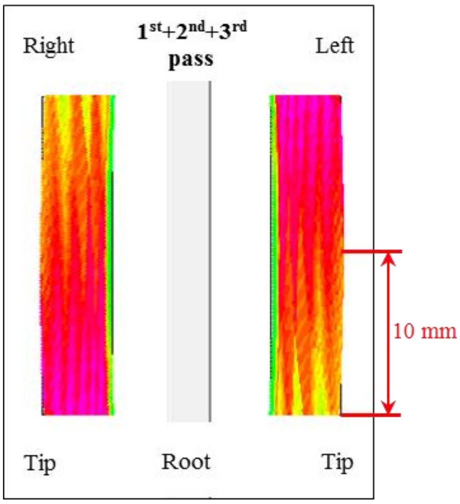
Considering frequency of contact in estimation of axial stroke

The axial stroke obtained using the analysis of contact region of workpiece and grinding wheel is not sufficient. The result does not take into account the frequency of contact at every point but only shows the region in which contact has taken place between the workpiece and grinding wheel at least once. Hence, the effect of frequency of contact between workpiece tooth and flank of threaded grinding wheel is considered to estimate the axial stroke. From Fig. 11, it can be seen that the frequency of contact in the lower portion of the left flank is relatively lower compared to the upper portion of the flank. The length of this region is estimated to be 10 mm (see Fig. 11).

$$\text{Ax Str (without considering frequency of contact)} = 7.3$$

$$\text{Ax Str (considering frequency of contact)} = 7.3 + 10 = 17.3$$

Hence the axial stroke in downward direction can be estimated to be 17.3 mm. During actual grinding, the downward stoke is 11.5 mm.



1st Pass + 2nd Pass + 3rd Pass

Fig. 11 Estimation of axial stroke by considering effect of frequency of contact

The difference between the actual value and simulation result is 17.3 – 11.5 = 5.8 which is close to the length of unground portion on the left flank of workpiece tooth, which is 6 mm. Thus, it would be possible to predict the necessary axial stroke and compare it with the maximum allowable limit without performing actual grinding tests.

CONCLUSIONS

- A new simulation tool has been developed to visualize and analyse the internal gear grinding process. By using this simulation tool, the region on the flank of threaded grinding wheel which is in contact with the workpiece tooth can be estimated.
- Using this result, the minimum axial stroke in upward and downward directions can be estimated. It has been found that in estimating the axial stroke, it is necessary to not only consider the contact condition but also frequency of contact at reach point. The axial stroke used in actual grinding is found to be lower than the axial stroke estimated using the simulation results. This explains the reason for the unground material remaining on the bottom left side of the tooth flank.
- This simulation tool is useful in checking the effect of different input parameters and grinding conditions on the output. This would be helpful in understanding the effect of various parameters like facewidth, number of threads of grinding wheel, crossed axes angle, without performing actual grinding tests.

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