Surface finishing method for tooth flank of heat-treated surface-hardened small gears using a gear-shaped tool composed of alumina-fiber-reinforced plastic

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1. Introduction

Compact geared motors are used in devices such as medical equipment. Those devices are often installed in silent environments and are used near people, so it is desired that compact geared motors are compact, strong, and quiet. In order to satisfy these demands, high-precision gears are needed.

Compact geared motors use heat-treated surface-hardened small gears. However, the accuracy of these gears deteriorates due to heat treatment distortion [1]. This causes strength deterioration of the tooth surface as well as vibration and noise. Recently, due to improvements in gear machining technologies, it is possible to remove the heat treatment distortion of the gears after heat treatment by surface hobbing the gear teeth with a carbide hob [2–6]. Using this method, although it is possible to realize a certain degree of accuracy, the surface roughness deteriorates, as shown in Fig. 1, because the tool marks from hobbing remain on the gear tooth surface [7]. Therefore, a finishing process for improving the gear tooth surface roughness is required that can eliminate the tool marks on the surface. However, tool marks on heat-treated gears are difficult to eliminate because the tooth surface is hard. In the case of normal-sized gears such as automotive gears, a finishing process is performed on the gear tooth surface by a gear honing method with a gear-shaped grinding tool [8-11]. Therefore, this honing process also seems effective as a tooth surface finishing process for small gears. Actually, B. Karpuschewski et al. describe examples of finishing methods for heat-treated small gears using a gear-shaped grinding tool, although the details are unknown [11]. However, a gear-shaped grinding tool for small gears (module 1 or less) is difficult to manufacture with sufficient strength because the tool's teeth are too small compared with the abrasive grains.

In a previous report [12], the authors proposed a new gear-shaped tool that is made of alumina-fiber-reinforced plastic (hereafter called ALFRP) in order to remove nicks that are formed at the edges of surface-hardened heat-treated small gears. The report showed that the ALFRP gear-shaped tool has sufficient strength even if its teeth are small because fibers are used. In this study, the authors propose a new finishing process for the tooth surface of surface-hardened heat-treated small gears using an ALFRP gear-shaped tool. A new surface finishing device suitable for small gears is proposed that has an oscillation/traverse system. Experiments on the tooth surface finishing process using this device and the ALFRP gear-shaped tool are performed. It is verified that the tool marks on the tooth flanks of the heat-treated surface-hardened small gear can be removed, and the surface roughness of the teeth can be improved. In addition, the processing mechanism of the ALFRP gear-shaped tool is discussed by observing the surface of the tool and the chips in the cutting oil.

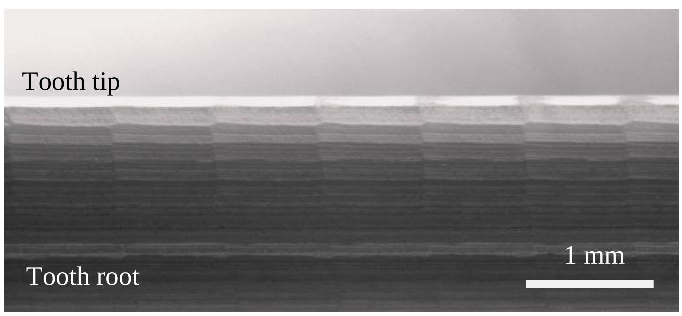


Fig. 1. Tool marks on tooth surface of work gear from hobbing

2. Characteristics of ALFRP and manufacturing method for gear-shaped tool

2.1 Characteristics of alumina long fibers and ALFRP

ALFRP is a compound material that is made by combining alumina long fibers with thermoset epoxy resin. The amount of fiber in the ALFRP used in this research is 60% by volume. As shown in Table 1, the tensile strength of alumina fiber with a diameter of 10 μm is 1.8 GPa. The Mohs scale of alumina fiber is 9, which means the hardness of the alumina fiber is the same as or more than that of hardened steel. For this reason, it is expected that ALFRP can be used in a removal tool for heat-treated surface-hardened gears. In addition, ALFRP has sufficient strength even if it is formed into small teeth on a small gear because alumina fibers are used. On the other hand, the hardness of ALFRP is not very high, so it can be machined using a cutting tool such as a carbide hob with a Rockwell hardness C-scale (hereafter called HRC) of 90. For this reason, it is possible to process ALFRP into a gear-shaped tool using a carbide hob. Thus, ALFRP is expected to function as a tool material for the tooth surface finishing of small gears and was chosen for this study.

Table 1
Characteristics of alumina fiber and ALFRP

(a) Characteristics of alumina fiber

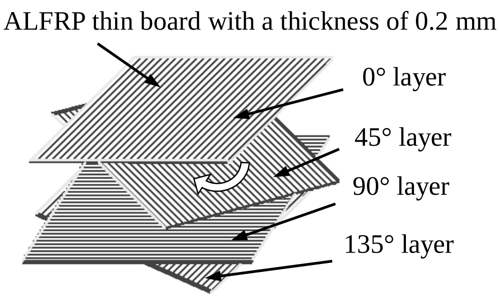
Chemical composition	Fiber diameter (μm)	Crystal form	Density (g/cm^3)	Tensile strength (GPa)	Tensile elastic modulus (GPa)	Mohs hardness
AL_2O_3 85 wt% SiO_2 15 wt%	10	γ-AL_2O_3	3.2	1.8	210	9

(b) Characteristics of ALFRP

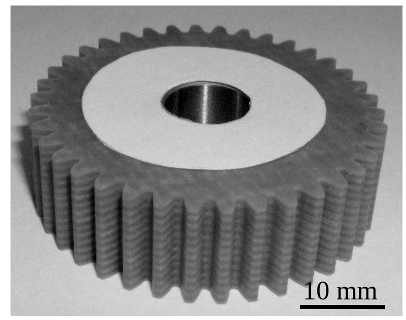
Density (g/cm^3)	Tensile strength (GPa)	Tensile elastic modulus (GPa)	Bending strength (GPa)	Compressive strength (GPa)	Rigidity module (GPa)	Interlayer shear strength (GPa)
2.4	1.35	137	1.56	2.2	7.25	0.13

2.2 Manufacturing method for ALFRP gear-shaped tool

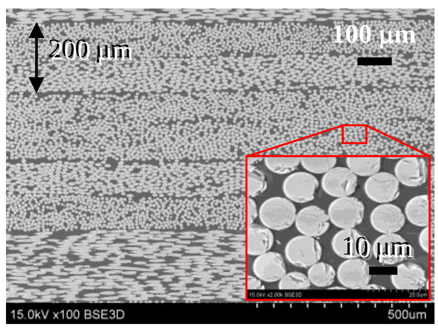
First, prepregs with a thickness of 0.1 mm consisting of alumina fibers with a diameter of 10 μm are adhered together, and thin ALFRP boards with a thickness of 0.2 mm are made. Next, as shown in Fig. 2(a), the thin ALFRP boards are laminated while changing the fiber direction by 45 degrees. Therefore, when the laminated board is manufactured into a gear-shaped tool, the direction of some alumina long fibers is close to the direction normal to the tool tooth surface. For this reason, the tips of the alumina fibers appear on the tool tooth surface, and these function as cutting edges. Moreover, this stacking method helps to prevent breakage of the teeth on a small gear-shaped tool. A thick board of ALFRP is made by bonding the thin boards with thermoset epoxy resin by heating under pressure. A cylindrical disk blank is manufactured by cutting the thick board. ALFRP disk-shaped blanks used in this study are 40 mm in outer diameter and 10 mm in thickness. Finally, the ALFRP gear-shaped tool is made from the disk blank using a carbide hob and a hobbing machine. A manufactured ALFRP gear-shaped tool is shown in Fig. 2(b). Figure 2(c) shows the lamination state of the ALFRP, where the cross section of the ALFRP thick board is magnified.



(a) ALFRP laminated board



(b) Manufactured ALFRP gear-shaped tool



(c) SEM photograph of cross section of ALFRP laminated board

Fig. 2. Manufacturing method for ALFRP laminated board and manufactured ALFRP gear-shaped tool

3. Gear tooth surface finishing device with oscillation/traverse system

3.1 Principle

The principle of the gear tooth surface finishing process with an oscillation/traverse system proposed in this report is shown in Fig. 3. A work gear and an ALFRP gear-shaped tool are meshed in parallel without backlash. The work gear drives the ALFRP gear-shaped tool, which is oscillated in the axis direction while being rotated. The tooth surface finishing process is performed by both sliding in the tooth depth direction due to the rotation of the gears and sliding in the tooth trace direction due to the oscillation movement. In the case without oscillation, the cutting action does not occur near the pitch point because sliding in the tooth depth direction does not occur there, which is a characteristic of an involute gear. As a result, the profile of the work gear in the tooth depth direction becomes convex in shape because the tooth surface near the pitch point is not removed. To prevent this, an oscillation in the axis direction is given to the ALFRP gear-shaped tool. The sliding is made even near the pitch point, and cutting action occurs there. On the other hand, the gear-shaped tool is moved slowly in the axis direction using a traverse device while being oscillated. In other words, the center position of the oscillation is gradually changed in the axis direction. Thereby, it is possible that the entire tooth surface of the work gear is finished uniformly.

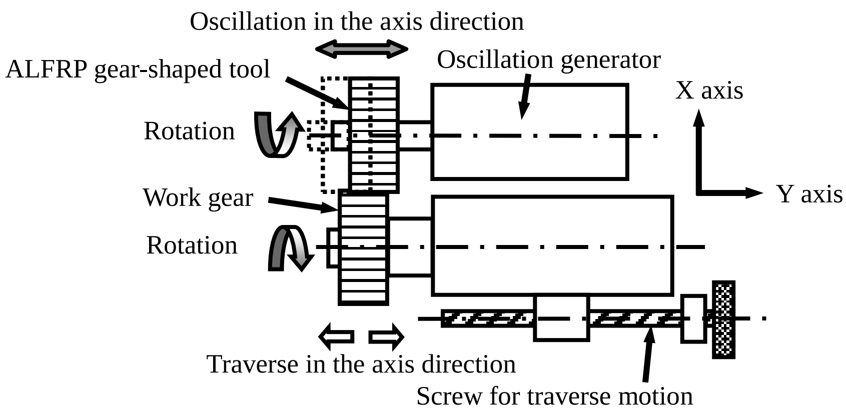


Fig. 3. Principle of the gear tooth surface finishing method using the oscillation/traverse system

3.2 Configuration

Figure 4 shows the gear tooth surface finishing device with the oscillation/traverse system. This equipment consists of a head stock installed in the horizontal feed slide (Y axis direction) and an oscillation device installed in the vertical feed slide (X axis direction). The main spindle is driven by a stepping motor, and they are connected by a disk coupler. The oscillation device has a slide base with a tool shaft where the ALFRP gear-shaped tool is set. This slide base oscillates in the axis direction. This oscillation is generated by a shaft with an eccentric pin [13], and the shaft is directly joined to a stepping motor with a disk coupler. A friction brake is set on the tool shaft, which gives a load between the work gear and the gear-shaped tool. The two stepping motors for the main spindle and the oscillation rotate synchronously while keeping the rotational speed ratio constant. The work gear is fixed on the mandrel of the spindle nose using a screw. The traverse feed motion of the work gear is generated by a ball screw that is installed at the side of the head stock.

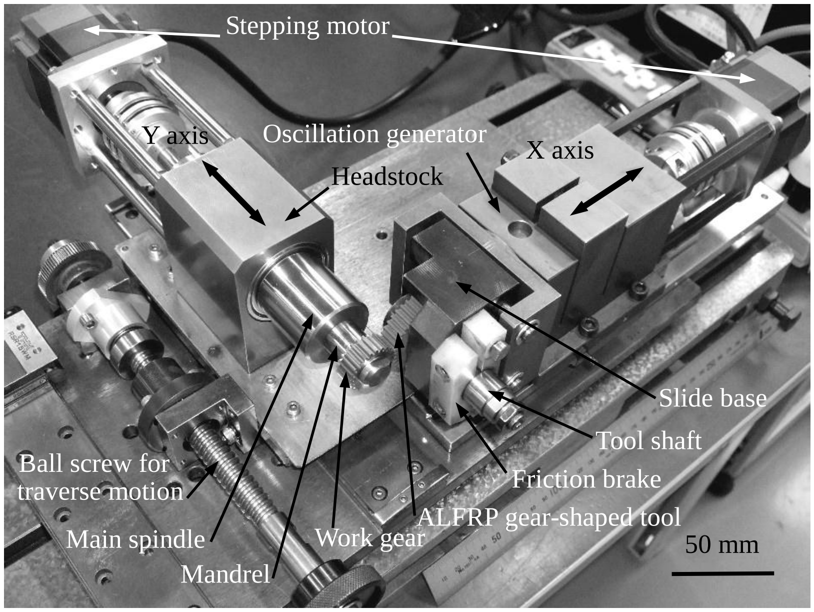


Fig. 4. Gear tooth surface finishing device with the oscillation/traverse system

4. Experiment on gear tooth surface finishing process

Experiments on the tooth surface finishing process are performed using the ALFRP gear-shaped tool and the gear tooth surface finishing device with the oscillation/traverse system. The work gears are the heat-treated surface-hardened small gears that were processed with the carbide hob. The finished tooth flank state of the work gear is evaluated by observation using a video microscope and by measurement of the tooth flank surface roughness and tooth flank form. The surface roughness is measured using a SV-C524 measuring device (Mitutoyo), and the tooth flank form is measured using a Type P26 measuring machine (Klingelnberg GmbH).

4.1 Experimental conditions

The specifications of the ALFRP gear-shaped tool and work gear and the experimental conditions are shown in Table 2. The work gears were pre-processed by a hob, were heat treated by carburizing-hardening and tempering to make the surface hardness HRC 53, and then were hobbed by a standard tooth profile carbide hob with a pressure angle of 20 degrees. The left side of Fig. 5 shows the state of the tooth surface of

Table 2
Specifications of the ALFRP gear-shaped tool and work gear and experimental conditions

(a) ALFRP gear-shaped tool and work gear

	ALFRP gear-shaped tool	Work gear
Normal module	1	
Normal pressure angle	20°	
Helix angle	0°	
Center distance	30.795 mm	
Number of teeth	38	24
Pitch circle diameter	38 mm	24 mm
Face width	10 mm	10 mm
Material	ALFRP	SCM415
Hardness		HRC 53

(b) Experimental conditions

Rotational velocity of work gear	15 rpm
Angular velocity of work gear	1.57 rad/s
Angular frequency of oscillation	312.48 rad/s
Amplitude of oscillation	2 mm
Traverse distance	6 mm
Friction torque	20 Ncm
Processing time	60 sec /60 sec in the clockwise and counterclockwise direction, respectively
Processing fluid	Cutting oil (Yusiron-cut BM618)

the work gear before the finishing process. The cutting marks from the carbide hob are observed on the tooth surface of the work gear. In this experiment, the ALFRP gear-shaped tool was processed using a carbide hob with the same rack profile form as that for processing the work gear. The experimental condition was set up considering the sliding velocity on the work gear tooth surface based on the theoretical formula proposed in the previous report [13]. Here, $\omega 2/\omega 1$ was set to prevent the synchronization of the oscillation and rotation as follows: the oscillation angular frequency of the ALFRP gear-shaped tool was $\omega 2$=312.48 rad/sec, and the rotational angular velocity of the work gear was $\omega 1$=1.57 rad/sec. The rotational velocity was set low because under high rotational velocity, the surface of the tooth tip and tooth root are removed more since the sliding velocities at the tooth tip and root are higher than near the pitch point. On the other hand, the angular frequency $\omega 2$ of oscillation is set high. This leads to an increase in the removal amount. It is also expected that the removal amount on the entire surface of the work gear tooth becomes uniform because the oscillation has a short wavelength. The ALFRP gear-shaped tool and the work gear are set at two positions so that the distance between the tooth width center of the ALFRP gear-shaped tool and that of the work gear is +3 mm or −3 mm. At each position, the ALFRP gear-shaped tool and the work gear are rotated for 60 sec in the clockwise and counterclockwise directions, respectively. Yusioron-cut BM618 was used as the cutting oil and was applied on the tooth flank of the work gear and the ALFRP gear-shaped tool just before processing.

4.2 Experimental results and discussion

4.2.1 Condition of work gear tooth surface

The left-hand side of Fig. 5 shows the state of the tooth surface of the work gear before the finishing process, and the right-hand side shows the tooth surface after the finishing process. Although tool marks from the hobbing process were observed on the entire tooth surface before the finishing process, they seem to be eliminated after the finishing process. The surface roughness measurement results before and after processing are shown in Fig. 6. The measurement is performed in the tooth profile direction near the face width center of the work gear and in the tooth trace direction near the pitch circle.

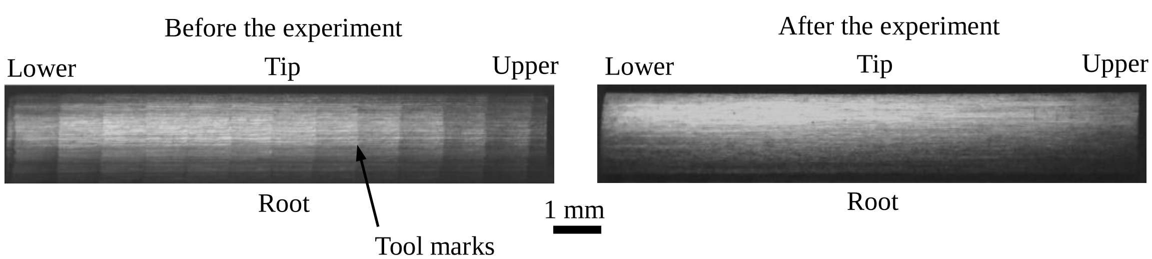
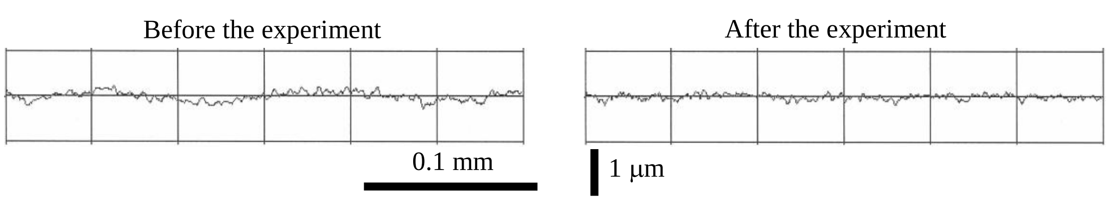
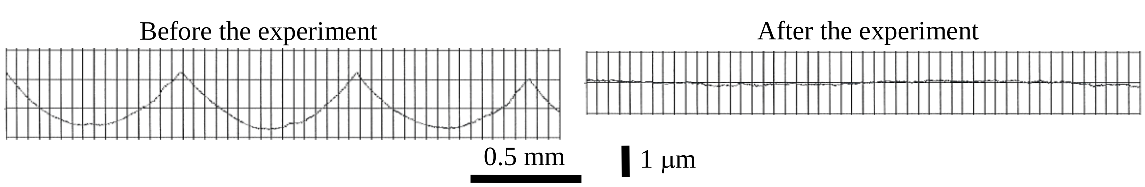


Fig. 5. Condition of left tooth flank of the work gear before and after the surface finish experiment



(a) Surface roughness of tooth flank of the work gear in the tooth profile direction



(b) Surface roughness of tooth flank of the work gear in the tooth trace direction

Fig. 6. Measured surface roughness of tooth flank of the work gear in the tooth profile and tooth trace directions before and after the experiment

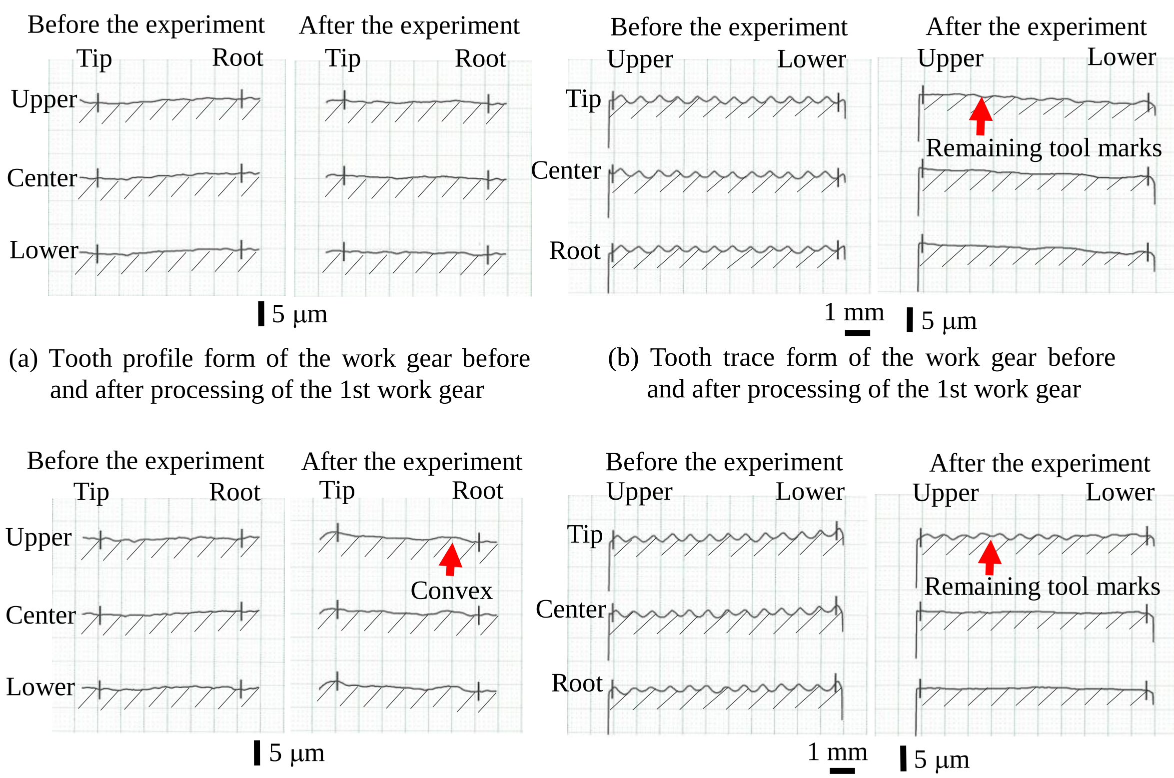
The maximum-height roughness Rz in the tooth profile direction was decreased from 0.51 μm to 0.40 μm by processing. In the tooth trace direction, it was reduced from 2.00 μm to 0.27 μm. Based on these results, it is verified that the surface roughness of the work gear can be made small by processing using the ALFRP gear-shaped tool and the gear tooth surface finishing device with the oscillation/traverse system.

4.2.2 The tooth profile form and tooth trace form

The measurement results for the tooth profile form and tooth trace form before and after processing are shown in Fig. 7. The tooth profile and the tooth trace of the work gear tooth surface before and after processing of the 1st work gear are shown in Fig. 7(a) and (b). Based on Fig. 7(a), it can be verified that there is no large change in the tooth profile form. Figure 7(b) shows that the unevenness due to the tool marks, which was 2.00 μm high before processing, was eliminated after processing. Thus, it could be verified that using the ALFRP gear-shaped tool and the proposed gear tooth surface finishing device, finishing of the heat-treated surface-hardened small gear is possible.

On the other hand, when Fig. 7(a) is observed in detail, it is seen that the tooth root side is removed more than the tooth tip side, and the tooth profile is slightly inclined. Moreover, when Fig. 7(b) is observed in detail, although the tool marks by hobbing have been completely eliminated after processing on the tooth root side, it is seen that tool marks with a height of 0.6 μm remain on the tooth tip side. This result shows that the removal action on the tooth tip side is less than that on the tooth root side. The reason is discussed in detail in the following section. It is considered that the difference in the velocity of the line of contact between the tooth tip side and the tooth root side influences this result.

Figure 7(c) and (d) shows the tooth profile and tooth trace form of the work gear before and after the processing of the 50th work gear. Based on Fig. 7(c), it is seen that the tooth profile form did not significantly change during processing. On the other hand, when observed in detail, the tooth root side is removed more than the tooth tip side. This tendency is the same as seen in Fig. 7(a). In Fig. 7(c), rounding occurs at the tip of the tooth. This position is equivalent to the position of the meshing end between the work gear tooth tip and the ALFRP gear-shaped tool tooth root. Near this domain on the ALFRP gear-shaped tool, the surface contacting the work gear is worn, but the other area is not worn. Therefore, it is considered that a gap exists in this domain of the ALFRP gear-shaped tool between the worn area and the non-worn area. Thus, this rounding of the tip of the work gear is considered to be caused by this gap on the surface of the ALFRP gear-shaped tool. A convex part with a height of 1 μm occurs near the tooth root of the work gear after processing, as shown by the arrow in Fig. 7(c). This domain is close to the boundary between one-tooth-pair engagement and two-teeth-pair engagement. In the one-tooth-pair engagement region, the tooth surface wear of the ALFRP gear-shaped tool is more than in the two-teeth-pair engagement region. Based on the difference between the one-tooth-pair engagement region (where wear is more severe) and the two-teeth-pair engagement region (with less wear), it is thought that such a convex surface occurs on the work gear tooth flank. This convex height is around 1 μm, which is satisfactory in practice based on our experience. The tooth trace form of the work gear before and after processing is shown in Fig. 7(d). The tool marks that existed before processing seem to be eliminated at the tooth root and at the center of the tooth after processing. On the other hand, they remain somewhat near the tooth tip. This tendency is the same as that in Fig. 7(b).



(a) Tooth profile form of the work gear before and after processing of the 1st work gear

(b) Tooth trace form of the work gear before and after processing of the 1st work gear

(c) Tooth profile form of the work gear before and after processing of the 50th work gear

(d) Tooth trace form of the work gear before and after processing of the 50th work gear

Fig. 7. Measured tooth profile and tooth lead form of the work gear before and after surface finishing process

From the above, although slight tool marks remained near the tooth tip, it was confirmed that the tool marks on the work gear tooth surface could be eliminated and the surface roughness could be improved using the proposed surface finishing method.

4.2.3 ALFRP gear-shaped tool after processing

Figure 8 shows the ALFRP gear-shaped tool after the surface finishing process. No failure is observed on the ALFRP gear-shaped tools. In the case of the grinding tool, gear-shaped tools with small teeth often break when they are used because the teeth are too small. However, as shown in Fig. 8, the ALFRP gear-shaped tool has sufficient strength due to the alumina fiber, even if the teeth are small.

Fig. 8. ALFRP gear-shaped tool after surface finishing process

5. Improvement of gear tooth surface condition

5.1 Method of increasing removal action near the tooth tip of the work gear surface

As seen in Fig. 7(a) and (c), the removal amount on the tooth tip side is less than on the tooth root side, and the tooth profile form of the work gear after processing is tilted. Moreover, as seen in Fig. 7(b) and (d), even if the tool marks are eliminated on the tooth root side, they often remain on the tooth tip side.

Figure 9 shows the locus of the gear-shaped tool and the contact points between the gear-shaped tool and the work gear. The contact part (line of contact) is shown by a point. As shown in Fig. 9, the interval of the line of contact between the work gear and the gear-shaped tool becomes narrow near the tooth root and wide near the tooth tip according to the characteristics of the involute gear. This means the movement of the line of contact between the work gear and the gear-shaped tool is faster near the tooth tip than near the tooth root. Although the contact part between the work gear and the gear-shaped tool theoretically becomes a line contact without any width, the line of contact actually deforms elastically and has a width of around 100 μm due to the tooth surface load since ALFRP is a viscoelastic material. The removal action occurs within that contact width. Since the movement of the contact point is slow on the tooth root side, a point on the tooth flank stays in the width of the line of contact for a long period of time. On the other hand, a point on the tooth surface receives the removal action in a short time at the tooth tip side, where the movement velocity of the line of contact is fast. For this reason, more removal action is given on the tooth root side than on the tooth tip side.

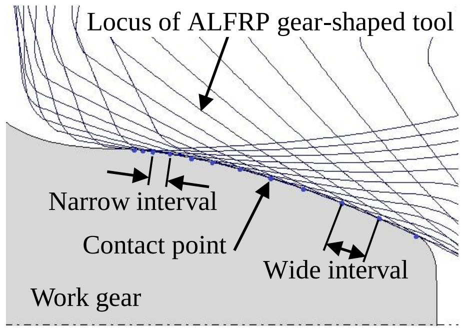
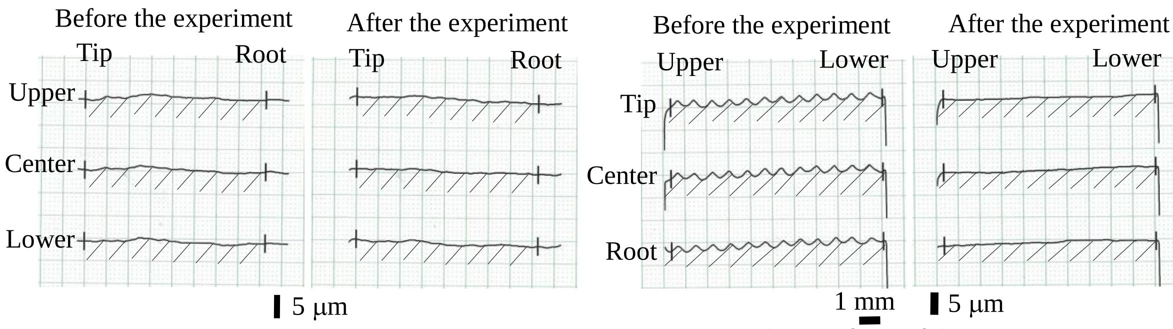


Fig. 9. Contact point on tooth surface of the work gear and ALFRP gear-shaped tool

In order to improve this state, a new method using the ALFRP gear-shaped tool with the modified tooth profile is proposed in this section. This ALFRP gear-shaped tool has a tooth profile such that the gear tooth root side is convex and the gear tooth tip side is concave. By using this method, the tooth tip side of the work gear meshes for a long period of time and receives more removal action than the tooth root side. A method of modifying the pressure angle is proposed to change the tooth profile form of the ALFRP gear-shaped tool. Although the pressure angle of the ALFRP gear-shaped tool used in the experiment in the previous section (Fig. 8) is 20 degrees, for the new ALFRP gear-shaped tool, the pressure angle is changed to 20 degrees, 20 minutes.

An experiment on the tooth surface finishing process was performed using this profile-modified ALFRP gear-shaped tool. These results are shown in Fig. 10. As shown in Fig. 10(a), there is no change in the inclination of the tooth profile form, and as shown in Fig. 10(b), in the tooth trace form, it is seen that tool marks do not remain from the tooth tip to the tooth root of the work gear. Based on the above, it is verified that the proposed ALFRP gear-shaped tool with the modified tooth profile is effective for processing the entire tooth surface of the work gear uniformly.



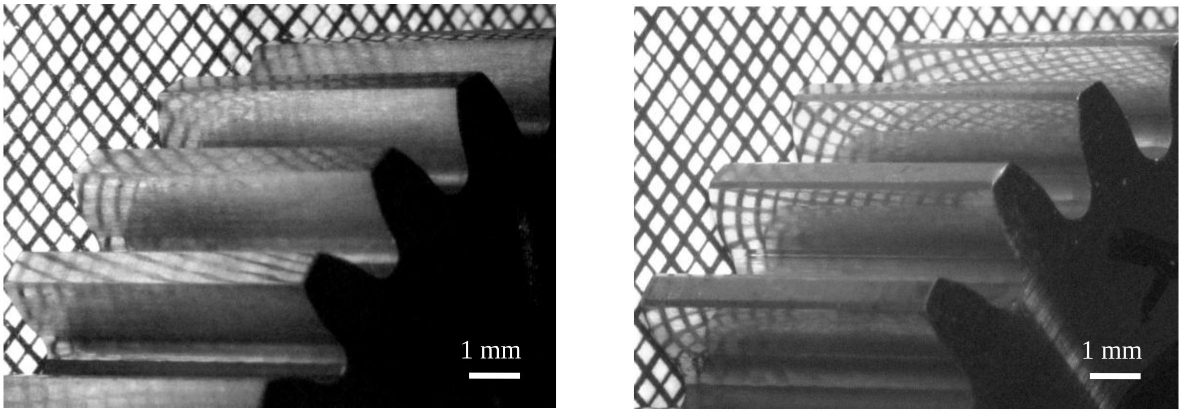
(a) Tooth profile form of the work gear (b) Tooth trace form of the work gear

Fig. 10. Tooth profile form and tooth trace form of the work gear before and after processing using the ALFRP gear-shaped tool with a modified pressure angle

5.2 Mirror-like surface processing

The tooth surface finishing process using the ALFRP gear-shaped tool is able to remove the tool marks on the gear tooth flank due to hobbing and to decrease the surface roughness as mentioned above. For this reason, it can potentially further decrease the surface roughness by lengthening the processing time and to make a mirror-like surface. This is verified experimentally. An experiment is performed where the processing time is doubled compared with the experimental conditions in Table 2(b). Two types of work gears are used in this experiment. One is the same as that in Table 2(a), and the other has a different hardness (HRC 62). The tooth flank after processing is shown in Fig. 11. It can be confirmed that the surface is mirror-like, and the grid line of the graph paper under the gear is reflected on the surface. Figure 12 shows the surface roughness of the work gear to be HRC 62. As shown in Fig. 12, as for the surface roughness in the trace direction of the work gear tooth flank, the maximum height roughness of 3.20 μm before processing has become as small as 0.24 μm after processing. From this, it is verified that mirror-like surface processing is possible using the ALFRP gear-shaped tool.

Comparing Fig. 11(a) and (b), the tooth surface of the HRC 62 work gear is glossier than that of the HRC 53 work gear. This indicates that the difference in hardness of the work gear influences the mirror-like surface condition [14].



(a) HRC 53 work gear (b) HRC 62 work gear

Fig. 11. Tooth flank surface of the HRC 53 and HRC 62 work gears after the experiment

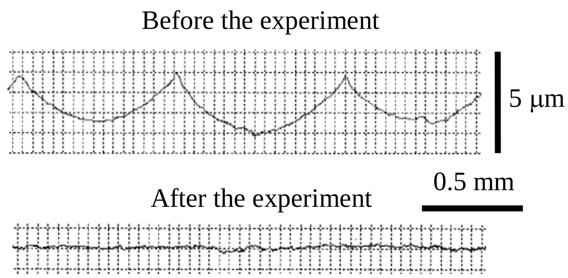
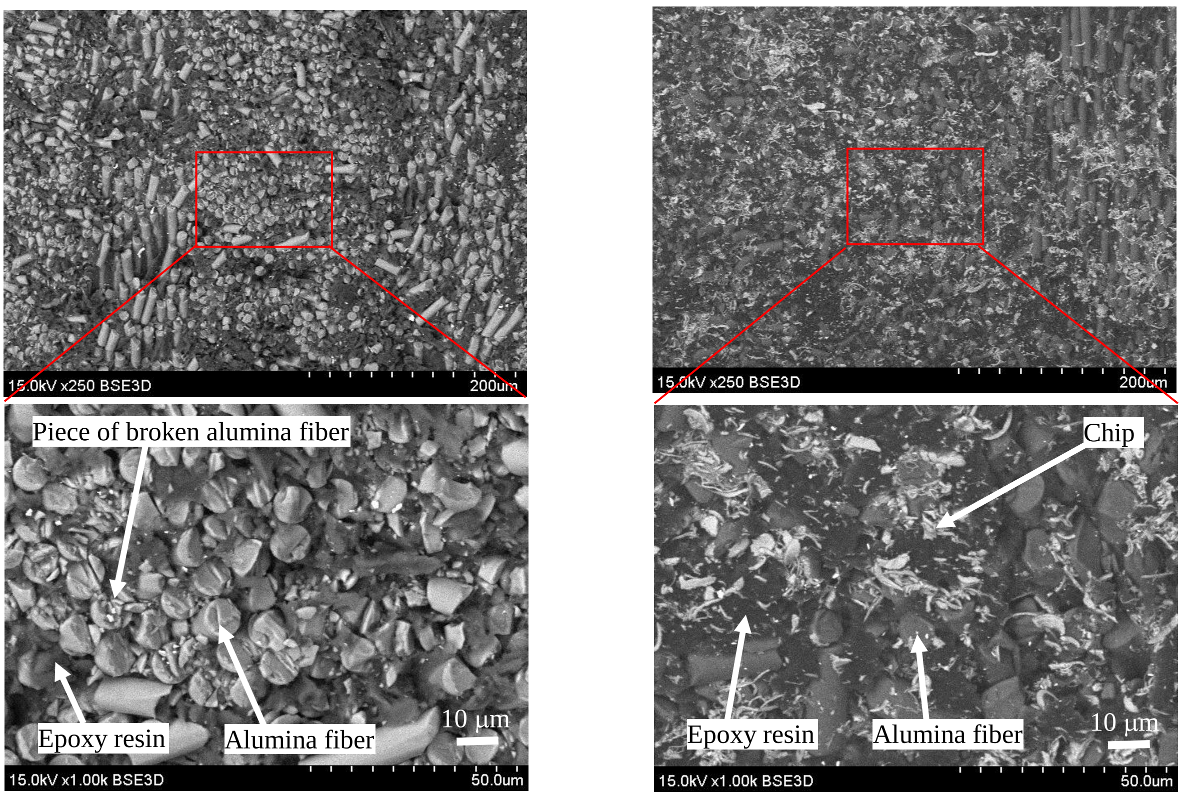


Fig. 12. Measured surface roughness of the tooth flank of the HRC 62 work gear in the tooth trace direction before and after the experiment

6. Observation of tooth surface of ALFRP gear-shaped tool and chips and discussion on the mechanism of the gear tooth surface finishing process

Scanning electron microscope (SEM) photographs near the tooth flank center of the ALFRP gear-shaped tool are shown in Fig. 13. The upper photograph of Fig. 13(a) shows the state of the tooth surface of an unused ALFRP gear-shaped tool made by hobbing with a carbide hob. It is observed that the tips of the alumina fibers are exposed from the epoxy resin. These fiber tips are considered to function as cutting edges. Moreover, when the magnified photograph on the lower side of Fig. 13(a) is observed, it turns out that the piece of alumina fiber crushed by hobbing is adhered among the alumina fibers held by the epoxy resin. The tooth surface condition of the ALFRP gear-shaped tool used for finishing the work gears is shown in Fig. 13(b). The result of the analysis by an energy dispersive X-ray spectrometer (EDX) clarified that the chips of the work gear and the epoxy resin of the ALFRP are adhered to the surface. The tips of the alumina fibers on the tooth flank of the ALFRP gear-shaped tool after the finishing process are partly covered by the epoxy resin, and the exposure of the alumina fiber tips is reduced.

On the other hand, although the clogging of chips is observed in a typical grinding process using a general whetstone, this was not observed with the ALFRP gear-shaped tool in Fig. 13(b). This is a difference between the general whetstone tool and the ALFRP gear-shaped tool.



(a) Before the experiment (b) After the experiment

Fig. 13. Surface of ALFRP gear-shaped tool before and after the experiment

An SEM photograph of the chips in cutting oil is shown in Fig. 14. Shear-type chips are observed that have a thickness of 2 μm, a width of 2 μm, and a length of 10 μm. Fine flow-type chips with a thickness of 1 μm and indefinite-type chips are also observed [15–17]**.** These indicate that the tips of the alumina fibers of the ALFRP gear-shaped tool function as cutting edges.

Figure 15 shows SEM photographs of the rubbed-off epoxy resin flakes extracted from the cutting oil after the experiment. It is thought that these are scraped off from the surface of the ALFRP when the tooth surface of the work gear has been removed by the ALFRP gear-shape tool. It is confirmed that some chips are discharged together with the epoxy resin because the chips are adhered to the surface of the epoxy resin.

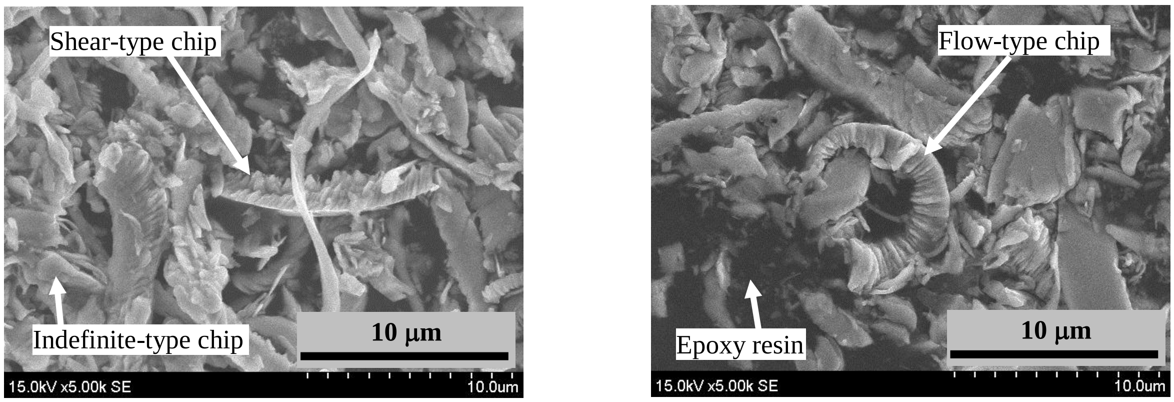


Fig. 14. Shaved-off chips of the work gear by surface finishing process using ALFRP gear-shaped tool

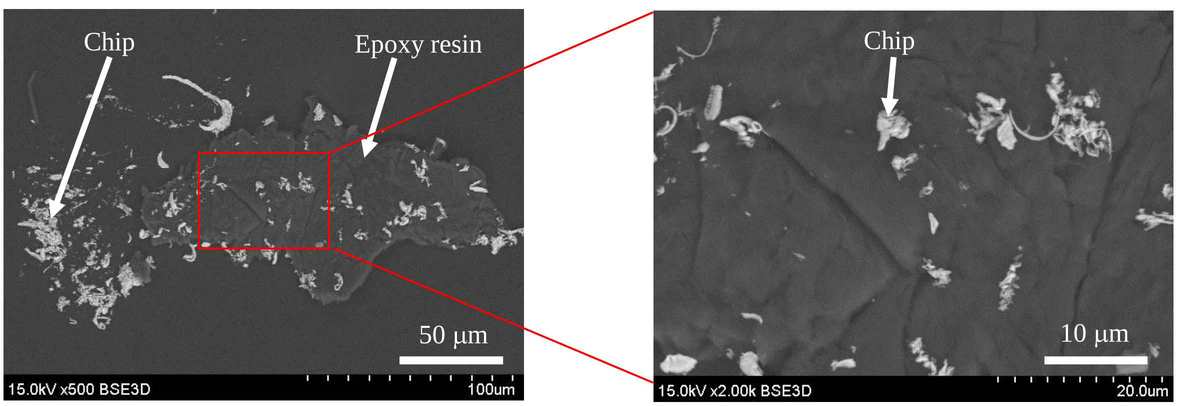


Fig. 15. Rubbed-off epoxy resin flake from ALFRP gear-shaped tool and adhered chip from work gear

7. Conclusion

In order to realize gear tooth flank surface finishing for heat-treated surface-hardened small gears, a processing method using the ALFRP gear-shaped tool and the gear tooth surface finishing device with an oscillation/traverse system was proposed in this report. Finishing process experiments on the tooth flanks of heat-treated surface-hardened small gears were performed. The obtained results are as follows:

(1) The finishing process method using the ALFRP gear-shaped tool and the gear tooth surface finishing device with the oscillation/traverse system was applied to the tooth flank of heat-treated surface-hardened small work gears hobbed by a carbide hob. The experimental results showed that the tool marks on the entire tooth flank of the work gear are eliminated, and the tooth surface roughness is decreased.

(2) A finishing process experiment was performed using the ALFRP gear-shaped tool, which has the same pressure angles as the work gear. The result showed that the removal amount on the tooth tip side becomes less than that on the tooth root side, and the tooth profile form is inclined. In order to solve this problem, a modified method is proposed where the pressure angle of the ALFRP gear-shaped tool is larger than that of the work gear. An experiment was performed using the modified tool, and it was verified that the proposed method is effective at processing the entire tooth surface of the work gear uniformly.

(3) The experiment clarified that the proposed surface finishing method can make the work gear tooth flank a mirror-like surface and can reduce the maximum roughness height to 0.3 μm.

(4) The tooth surface of the ALFRP gear-shaped tool and the chips in the cutting oil were observed using SEM. Shear-type chips, flow-type chips, and indefinite chips were observed. This indicates that the tips of the ALFRP alumina fibers function as cutting edges, and therefore, the tool marks on the work gear tooth surface were eliminated.

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