Shaping of Helical Gear by Two-Step Cold Extrusion*

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The authors previously proposed a two-step cold extrusion method for shaping spur gears. This method was applied to shape helical gears in this study. A specially designed die was used for shaping helical gears in two steps. The specifications of the gears examined were as follows: module $m = 1.5$, number of teeth $Z = 18$, helix angle $\beta = 20^\circ$. The material used for the experiment was low-carbon S15C steel. Workpieces with different inner diameters were formed to examine the effect of a reduction in cross-sectional area. To examine the effect of reductions in area, extrusion was carried out in three ways: 1) using a mandrel whose diameter is equal to the inner diameter of the workpiece; 2) using a mandrel whose diameter is smaller than the inner diameter of the workpiece; and 3) using no mandrel. Helical gears with complete teeth were formed in almost all the shaping conditions examined, even when the reduction in area was as low as 7% and punch pressure was relatively low. [doi:10.2320/matertrans.P-MRA2008803]

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1. Introduction

Gears are typically manufactured using hobbing machines, gear shapers, and other cutting, removing, and processing machines. The large amount of chip material generated and the relatively long time required for processing are hindering the goal of cost reduction by mass production. To overcome these disadvantages, some studies have been carried out on gear shaping by plasticity processing.^{1,2)}

The authors have conducted a series of studies on gear shaping using extrusion methods. These studies show that a high reduction in cross-sectional area, about 30% or more in the case of one-step extrusion³⁾ (hereafter called the conventional method), is required to form a complete gear. On the other hand, a two-step extrusion method proposed by the authors^{4,5)} can be used to form complete gears with a reduction in area of only about 22%. Moreover, extrusion without using a mandrel or extrusion using a mandrel whose diameter is smaller than the inner diameter of the workpiece can be carried out to form complete gears with a considerably smaller reduction in area, about 7%. Such favorable results were obtained because the die shape adopted in the two-step method promotes the flow of material towards the circumference of the gear, that is, towards the tips of the gear teeth.

The above-mentioned results are relevant to the shaping of spur gears. The advantage of the two-step extrusion method is that it is more effective in shaping helical gears whose teeth are twisted. In this study, we applied the two-step method to the shaping of helical gears using S15C steel, a commonly used low carbon steel. We compared the observed results with previously reported results obtained using the conventional one-step method.

2. Experiment

2.1 Experimental equipment and specifications of helical gear

Figure 1 shows a schematic cross-sectional view of the experimental apparatus. First, a set of workpieces consisting

Fig. 1 Schematic illustration of experimental equipment (cross section).

of a front workpiece 4 and rear workpiece 5 was inserted into the die container 1. This configuration is shown on the left side of the centerline in the figure. The workpieces were pressed by the punch 2 and extruded through the die 1, so that gears were formed. This forming process is shown on the right side of the centerline in the figure.

The die, made of SKD11 steel, was heat-treated after machining. The gear teeth were shaped by electrical discharge machining, with lapping performed on areas where needed. The inner diameter of the container D_c is equal to the diameter of the addendum circle of the gear and the outer diameter of the workpiece d_o . Accordingly, this die does not reduce the outer diameter of the workpiece.

When the inner diameter of the workpiece d_i was 10 mm or more, a floating-type mandrel was inserted into the inner space for shaping. There were nine different mandrel diameters from 10 mm to 18 mm at 1 mm intervals. The shaping experiment was carried out using a compression testing machine with a capacity of 1.9 MN. Load and stroke measurement devices were incorporated into the die unit.

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Table 1 Specifications of helical gear.

	First step	Second step
Module m/mm		1.5
Number of teeth Z		18
Helix angle $\beta/^\circ$		10 20 30
Addendum d_k/mm	32.00	32.00
Deddendum d_r/mm	27.25	25.25
Tooth depth h/mm	2.38	3.38
Rack shift coefficient χ	+1.33	+0.67

Fig. 2 Schematic illustration of the tool part of the die used to form the tooth space of a helical gear.

Table 2 Mechanical properties of S15C material.

	F value MPa	n value	Hardness HV	$\bar{\sigma}$ MPa
S15C	715	0.215	117	560.9

The gear studied has module $m = 1.5$, number of teeth $Z = 18$, and helix angle $\beta = 20^\circ$. The other main specifications of the gear are given in Table 1.

2.2 Die configuration

A gear tooth formed by the two-step extrusion method is shown schematically in Fig. 2(a), and compared with a tooth formed by the conventional one-step method (b). The first-step part of the teeth shown in (a) has a positive addendum modification of +0.67 with reference to the target value.

2.3 Workpiece

The material used for the experiment is low-carbon S15C steel, whose mechanical properties are given in Table 2. Here, $\bar{\sigma}$ represents the mean flow stress corresponding to a strain range between 0 and 1 and is calculated from a true-stress versus true-strain curve obtained by the compression test. After an annealing treatment, a solid cylindrical or tubular workpiece, as shown in Fig. 3, was machined.

A phosphate and metal soap coating was applied to the workpiece for lubrication, and a thin layer of Johnson Wax JP103 was also applied before the experiment. The friction shear factor of the workpiece in this state was found to be about 0.13 using a ring compression test.

Fig. 3 Size and dimensions of workpiece.

Fig. 4 Load-stroke curve.

3. Experimental Results and Discussion

3.1 Load and products

A curve showing the relationship between punch load and stroke measured during the extrusion process is shown in Fig. 4. There is a change in the slope of the curve within the range corresponding to the two-step part of the die (zones ①, ②, and ③ in the die profile). This change is characteristic of the two-step extrusion method. For comparison, the broken line in the figure shows the results of the conventional method. In the case of the two-step extrusion, the slope of the curve is small in the flat part of the profile (② in Fig. 4) between the first step ① and the second step ③, and then increases so that the maximum load becomes greater than that of the conventional method. The observed results can be explained by the following characteristics of the two-step method compared with those of the conventional method: the die structure in the two-step method promotes material flow especially in the vicinity of the teeth; the work hardening of the material is prominent; and there is a larger contact area between the material and the die in the tooth part, such as zone ②. Even when gears of the same specifications are formed from a workpiece of the same dimensions, the shaping of the tooth part is significantly improved in the two-step method because of the higher load experienced. The experimental results also indicate that larger inner diameters of the workpiece cause higher loads. The larger the inner diameter, the greater the change in cross-sectional area (reduction in area) during the shaping.

Fig. 5 Photograph of products (various d_i).

Fig. 6 Flow of material cleared by grid line.

The photographs in Fig. 5 show some examples of products. The upper photograph shows a front, a rear, and a third workpiece. The third workpiece is still in the process of shaping. A gear with completely formed teeth was obtained from the rear workpiece. The lower photograph shows products formed from workpieces having different inner diameters. Successfully formed products were obtained regardless of inner diameter.

A workpiece was cut in half longitudinally to examine the flow of material, and grid lines with 1 mm spacing were scribed on the cut plane. The product obtained from this workpiece is shown in Fig. 6. Although the grid remained almost unchanged in the vicinity of the inner diameter, the grid was distorted significantly in the vicinity of the tooth profile. The same experiment carried out using the conventional method revealed the distortion of the grid throughout the area between the inner diameter and the tooth part. The comparison of the grid distortion patterns indicates that the flow of material is concentrated near the tooth profile in the two-step method.

3.2 Process of workpiece deformation

When shaping along the tooth profile of the die starts at the forefront of the workpiece, the workpiece begins to rotate according to the twist angle of the die ($\beta = 20^\circ$). At the rear end of the workpiece, which has not yet reach the tooth space,

Fig. 7 Twisted angle of the inner surface of a hollow workpiece, measured along the longitudinal direction.

this rotation is impeded by the friction of the workpiece with the punch and the container wall. Therefore, the workpiece is twisted during the shaping process.

This type of twisting was previously confirmed in the conventional one-step extrusion method.³⁾ To investigate this phenomenon in the two-step method, a workpiece with longitudinally scribed lines on the inner diameter surface was prepared. Then the product formed from the workpiece was cut in half along the longitudinal direction, and the distortion of the scribed lines was measured.

The results of this test are shown in Fig. 7 as solid and broken lines for the two-step and conventional methods, respectively. The observed twisting was smaller in the two-step method than in the conventional method. Although a detailed explanation is not given for this observation, the load experienced by the workpiece while passing through zone ② is relatively small in the two-step method, as indicated from the difference in the load-stroke curves shown in Fig. 4. Therefore, it may be easier for the workpiece to rotate in the die in the two-step method than in the conventional method.

3.3 Effect of inner diameter of workpiece on shaping

The inner diameter d_i of the workpiece was varied to investigate the effect of a reduction in area on shaping.

Even when the teeth in the longitudinally central part of the workpiece are completely formed, the teeth near the forefront and rear end of the workpiece may not yet be completely formed, as is shown schematically in Fig. 8. The widths of defective teeth X , Y and X' in the figure are used hereinafter

Fig. 8 Schematic illustration of shaped tooth along longitudinal direction (cross section).

Fig. 9 Width of defective tooth with respect to reduction in cross-sectional area.

as indicators of the shaping condition. The figure depicts a rear workpiece in the middle of the shaping process. If a third workpiece is inserted and the rear workpiece is extruded, the defective widths of the product will be X' at the forefront and Y at the rear end. Workpieces further inserted consecutively for shaping will have defective widths denoted as X' and Y .

The relationship of defective widths X' and Y to reduction in area is shown in Fig. 9. The numerical value shown above each thin vertical line in the figure represents the inner diameter of the workpiece. The larger the diameter, the greater the reduction in area. The figure suggests that the diameter does not substantially affect the shaping condition.

When the inner diameter of the workpiece was zero (solid cylindrical workpiece), the smallest reduction in area of about 20% was obtained by the two-step method. Still, the teeth in the longitudinally central part of the product were completely formed. The results obtained by the conventional method are also shown in Fig. 9 as open symbols. Using the conventional method, a complete set of teeth were formed in the longitudinally central part of the workpiece having an inner diameter of 15 mm or greater (corresponding to a reduction in area of about 27%, as shown by the vertical broken line). However, defective-tooth widths were fairly large at both ends of the product when using the conventional method. These results clearly indicate that the shaping condition is improved by the two-step method.

Punch pressure σ_p , obtained by dividing the maximum load during shaping by the cross-sectional area of the punch, is shown in Fig. 10 as a function of reduction in area. In the two-step method, complete teeth were formed at a reduction in area of 20% or more. As for the conventional method, the open symbols in the figure represent products with defective teeth and the solid symbols represent products with complete teeth, which correspond to a reduction in area of 27% or greater. In both extrusion methods, complete teeth were formed when the punch pressure was about 600 MPa or more. When both extrusion methods are compared for the same reduction in area, the two-step method results in a high punch

Fig. 10 Maximum punch pressure with respect to reduction in cross-sectional area.

pressure of about 600 MPa even for a reduction in area of 20%. Thus, it can be said that gears with complete teeth can be formed under this punch pressure regardless of the extrusion method.

3.4 Shaping without mandrel and using small-diameter mandrel

In the two-step extrusion method, gears with complete teeth could be formed even with a cylindrical workpiece, which had the lowest reduction in area. To confirm that a completely formed product could be obtained even for a lower reduction in area, the following two experiments were carried out.

(1) Shaping with no mandrel in the inner diameter area of the workpiece. This allows the material to flow in the radially inward direction.

(2) Shaping using a mandrel whose diameter is smaller than the inner diameter of the workpiece (small mandrel). This allows the material to flow into the space between the mandrel and the inner diameter of the workpiece.

Figure 11 shows workpieces that were recovered in the middle of shaping without using a mandrel. The workpieces were cut in half longitudinally. The inner diameter of each workpiece was reduced because of the induced radially inward flow of the material as it was extruded through the die.

Teeth were formed incompletely in some products because of imperfect material flow. To investigate this phenomenon, the products were cut longitudinally in the middle part to measure the actual height of the tooth h' on the cut surface. The ratio between h' and the target height of the tooth h was calculated and used as a measure of the shaping condition. This ratio, A , is called the formability index. Considering the practical cases of continuous extrusion, the formability index was calculated using rear workpieces and plotted against reduction in area in Fig. 12. For both cases of shaping without a mandrel and shaping with a small-diameter mandrel, reduction in area was calculated by averaging the inner diameters measured on the front and end faces of the product. The solid symbols in the figure represent products with complete teeth, having a formability index of 100%, and

Fig. 11 Photograph of products without using mandrel (longitudinal cross section).

Fig. 12 Formability index with respect to reduction in cross-sectional area.

the open symbols represent products with incomplete teeth, having a formability index less than 100%. In the conventional one-step method, a reduction in area of 27% or more was required to form complete teeth. In the two-step method using a normal mandrel, a minimum reduction in area of about 20% was required. In both the cases of two-step extrusion using no mandrel and two-step extrusion using a small-diameter mandrel, the required minimum reduction in area was as low as about 7%.

Defective widths measured near the end faces of the products formed without using a mandrel are plotted in Fig. 13 against formability index measured at the middle part of the products. Again, these values were measured in rear workpieces. As shown in the figure, formability index decreases when the reduction in area is below 7%, and defective widths increase as reduction in area decreases. This means that the shaping condition degrades as reduction in area decreases. The workpieces with low reductions in area have large inner diameters, and this leads to a large flow of material in the radially inward direction. For workpieces having an inner diameter of 15 mm or less, which corresponds to a reduction in area of 10% or more, products fit for practical use with sufficiently small defective widths X' and Y were formed.

Figure 14 shows the punch pressure required for gear shaping using different extrusion methods. Solid and open symbols represent products with complete teeth and those

Fig. 13 Shaping condition with respect to reduction in cross-sectional area (no mandrel).

Fig. 14 Maximum punch pressure with respect to reduction in cross-sectional area.

with incomplete teeth, respectively. In the conventional extrusion method, the minimum required values for complete shaping are about 27% for reduction in area and about

Fig. 15 Example of continuous shaping.

600 MPa for punch pressure. In the two-step extrusion method, these values are about 7% and 500 MPa, respectively.

3.5 Possibility of continuous extrusion and precision of products

To confirm the practical applicability of the two-step method, continuous extrusion was carried out by placing workpieces directly into a die one after another. As shown in Fig. 15, complete helical gears were shaped continuously. Load was kept almost constant during the extrusion.

The precision of the products was also investigated. The measured values of pitch error and radial runout fall within the range between ranks 2 and 4 in the old JIS standard and are thus acceptable for practical use. However, helix angles are $20'$ to $30'$ smaller than expected in every product. This is caused by the load applied during extrusion being in a direction that leads to a reduction in helix angle. Some correction is therefore necessary. No difference in precision was found between the conventional and two-step extrusion methods.

4. Summary

Helical gears with complete teeth can be formed with a two-step cold extrusion using low-carbon steel workpieces. With the aim of applying the two-step method to gears with low reductions in area, shaping was carried out using no mandrel as well as using a small-diameter mandrel. As a result, gears with complete teeth were formed. The main results obtained within the range of the experimental conditions are summarized as follows.

- (1) The minimum reduction in area required for the material to flow completely to the tips of the gear teeth is about 7% for a punch pressure of 500 MPa. Gears almost free of defects were formed at reductions in area of 10% or more.

- (2) The punch pressure required to form complete teeth can be reduced in the two-step method by about 20% from 600 MPa (for a reduction in area of 27%) required in the conventional method.
- (3) A helical gear is formed as the material is twisted and extruded along the tooth profile of the die. The observed twisting is much smaller in the two-step method than in the conventional method.

The two-step extrusion method, which allows continuous extrusion at low reductions in area and low punch pressures (*i.e.* low loading) as well as free selection of tooth width, is useful for shaping helical gears and can be used for processing practical steel materials.

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